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LOW COST FIBER OPTIC CABLE ASSEMBLIES FOR LOCAL DISTRIBUTION SYSTEMS

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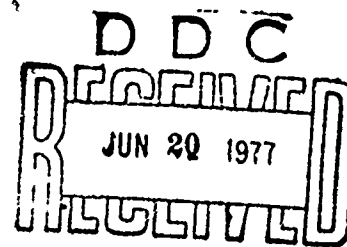
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes the results of one year effort to develop a low cost fiber optic cable using plastic clad silica fibers. As part of the program, silica core and plastic cladding materials were evaluated with respect to optical attenuation, mechanical properties, chemical properties, and radiation hardness. Fabrication techniques were developed and means to minimize excess cable loss evaluated. Uncabled fibers were fabricated with attenuations as low as 5.5 dB/km at .79 μ m microns.			

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20. (Continued)

Three cable designs were developed; one with central strength members, one with external strength members, and one with central strength members and an external braid. These designs, though developed for plastic clad silica fibers, are well suited to use with low loss doped silica fibers as well.

The cables were fabricated in two phases. In the first phase, short lengths (1/3 km) of the three designs were fabricated and subjected to optical and mechanical evaluations. Based on the results of these tests, the third design was eliminated since it was more costly and offered no advantages over other designs. In the second phase, final cable models of the central strength member and the external strength member designs were fabricated in lengths from 1/3 km to 1 km. The final models were subjected to optical, mechanical, environmental, and radiation evaluations.

The cables met or exceeded most of the program goals. Attenuation of cabled fibers averaged less than 10 dB/km @.79 microns, impact resistance was in excess of 1.5 ft-lbs., bend and twist testing resulted in no broken fibers at 2000 cycles, tensile strength exceeded 400 lbs., moisture exposure resulted in minimal increases in attenuation, and the fibers exhibited radiation hardening after initial high doses. In addition, cost projections indicate that fiber optic cables will be competitive with conventional CX4566 conductor by 1978 and by 1979-1980 will offer cost savings of 30-50%.

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1.0 INTRODUCTION

The potential advantages of fiber optic communication systems are well known. For Army tactical field applications these include increased bandwidths with associated larger repeater spacings than with conventional metallic conductors. Besides being of lighter weight and smaller size than conventional cables, fiber optic cables are impervious to EMI and EMP, and are tempest free.

The U. S. Army Electronics Command, Fort Monmouth, New Jersey, has initiated a program to develop "Low Cost Fiber Optic Cable Assemblies for Local Distribution Systems." The program includes two phases; the first was a one year effort to perform initial cable development and the second will be to develop cable assemblies including cables and compatible connectors. This report describes ITT's effort on the first phase performed under Contract #DAAB07-75-C-1328. The work was being performed by ITT's Electro-Optical Products Division (EOPD) in Roanoke, Virginia.

The general objective of the program is the development of low cost fiber optic cables and connectors for use in tactical communications systems in lengths of one kilometer or less. The cable assemblies are for use in systems which will operate at selected wavelengths in the 6,000 to 10,600 Angstroms for both analog and data transmission with data rates to 20 megabits per second. The cables are required to be lightweight, flexible, and rugged enough to withstand tactical field army requirements. Furthermore, the cable was to be designed so that production quantities can be expected to be cost competitive

with conventional metallic conductor cables. Specific objectives for the first phase of the program are summarized in Table I.

ITT's approach to producing low cost optical cables for the Army tactical field environment is based on the use of plastic clad silica fibers. The use of these fibers is attractive because they can be produced by a single preform drawing technique with attenuation below 10 dB/km from materials now available for less than 1 cent per fiber foot. Furthermore, they have moderately high numerical aperture, above .27, and can be produced with core diameters of 125 μ or above. Fiber diameter of 125 μ was selected to minimize coupling losses and maintain flexibility. Smaller fibers result in larger optical coupling losses and larger fibers are less flexible. In addition, a fiber diameter of 125 μ has been accepted by a number of fiber manufacturers as an informal industry standard for both plastic clad silica and all-glass fibers. At the present time, it is desirable from a connector standpoint to maintain a degree of diameter standardization between plastic clad silica and all-glass fibers. As product lines proliferate however, it is expected that two or more standard sizes may develop. Finally, plastic clad silica fibers exhibit low susceptibility to radiation induced attenuation as the pure silica materials used in their manufacture have the lowest susceptibility to radiation induced attenuation of any core material presently being considered for optical fibers.

The completed effort also included fiber optimization and cable development. The approach included:

- a. Investigation of basic core and cladding materials which appeared to be the most promising from the standpoint of enabling the drawing of multimode fibers with optical and physical properties consistent with the program objectives.

TABLE 1.1
CABLE OBJECTIVES

Physical:

a. Length	1/3 kilometer - 1 kilometer
b. Number of fibers	6
c. Size overall	.250 inch
d. Weight	100 lb/km

Transmission:

a. Wavelength	6000 - 10,600 Angstroms
b. Attenuation (min. 3 mutually agreed wavelengths in range including 8200 Å)	50 dB/km (Required) 20 dB/km (Desired)
c. Data transmission	
(1) Bit rate	20 megabits/second
(2) Rise and fall times	4 nanoseconds
(3) Pulse flatness	3 dB peak to peak variation from voltage output level
c. Numerical aperture	.27 minimum per kilometer length

Mechanical:

a. Tensile strength	400 lb
b. Vibration, Temperature cycling, Moisture resistance, Immersion	MIL-STD-202
c. Fungus	MIL-STD-810
d. Flexing, Impact, Twisting	MIL-C-13777

Nuclear survivability:

10^3 to 10^5 roentgens level (Cobalt 60)
10^{12} to 10^{14} neutrons/cm ² (1 Mev equivalent)

2.0 FIBER FABRICATION AND EVALUATION

Two processes have been reported for fabricating plastic clad silica fibers. In one process the silica core is coated with a liquid which hardens to form a cladding; in the other process molten plastic is extruded over the silica core. The liquid cladding approach yields a cladding which is in intimate contact with the core surface, while extrusion can be used to produce either a tight or a loose cladding. In both cases the plastic must have a lower index of refraction than the core to confine light at the core-plastic interface.

Since the light, except for evanescent fields, is confined to the core, it is the core attenuation which contributes most to the overall fiber attenuation. Thus, the cladding can have a relatively high attenuation. In the case of loose claddings, as surface contact area is fairly low, materials with attenuations between about 10,000 and 100,000 dB/km can be used to produce fibers with attenuations below 50 dB/km. For tight coatings the cladding influence is greater and attenuation in about the 1000 to 10,000 dB/km range is required to meet program objectives. For melt extrusion, fluoropolymers are the materials of primary interest because of the refractive index requirements. (Teflon^R refractive index is 1.35, silica refractive index is 1.46, fiber numerical aperture is .55). For dip coating, encouraging results have been reported with suspension of fluoropolymers, such as Kynar and with silicone resins. (Silicone RTV refractive index is 1.43, fiber numerical aperture is .30). With suspensions, curing is required to evaporate the carrier chemical, while silicone

resins are available which cure with time at room temperature (room temperature vulcanizing) and whose curing can be accelerated by elevating temperature.

The best results reported to date - under 5 dB/km - have been achieved with Teflon^R extruded plastics and silicone resin RTV. The attenuations achieved with fluropolymer dip coatings have been in the neighborhood of 50 dB/km due to the intrinsic properties of the material.

The design of optical fibers must take into account not only intrinsic attenuation and dispersion, but also numerical aperture, susceptibility to cabling induced attenuation, and radiation hardness. This section describes ITT's fiber fabrication and material evaluation effort.

2.1 Fabrication Approaches

Plastic optical cladding materials may be applied to fibers by a variety of processes including extrusion, dip coating, spray coating, electrostatic coating, and plasma deposition. The investigation of these techniques was initiated prior to the start of the present program. In-line extrusion and dip coating of plastic materials is now performed routinely at EOPD, and other techniques such as spray coating, electrostatic coating, and plasma deposition are under investigation.

To produce plastic-clad silica fibers of high quality and low cost, in-line extrusion and dip coating techniques were investigated in detail during the first six months of this program. The first

technique consists of in-line extrusion of a plastic optical cladding over the as-drawn fiber. The second technique consists of applying the optical cladding in-line by dip coating and subsequent extrusion of a protective coating. The dip coated cladding material and the extruded protective coating have been applied in a two-step operation and in-line in a single operation.

The selection of the technique for application of specific plastic cladding and protective coating materials depends on their mechanical properties, working temperature, viscosity, and curing temperature. Some cladding materials that are extrudable cannot be applied by dip coating and vice-versa.

The basic fiber drawing set-up is shown in Figure 2-1. The system consists of a preform collet which is mounted on a vertical feed, an oxyhydrogen flame or graphite resistance furnace heat source, and a mechanism to pull and take up the fiber. To achieve in-line extrusion and dip coating of plastic cladding materials, an extruder or dip coater, or both, are positioned between the heat source and the drawing-takeup mechanism. Fiber diameter uniformity is maintained by accurately controlling the temperature of the heat source. Fiber diameter variations ranging from ± 5 to 10% have been measured with the oxyhydrogen burner system and variations of less than 1% have been achieved with the graphite furnace.

2.1.1 In-Line Extrusion Coating Technique

In-line extrusion coating of the optical cladding materials was accomplished by positioning a 3/4" screw extruder between the heat source and the drawing takeup. The process consists of forcing a

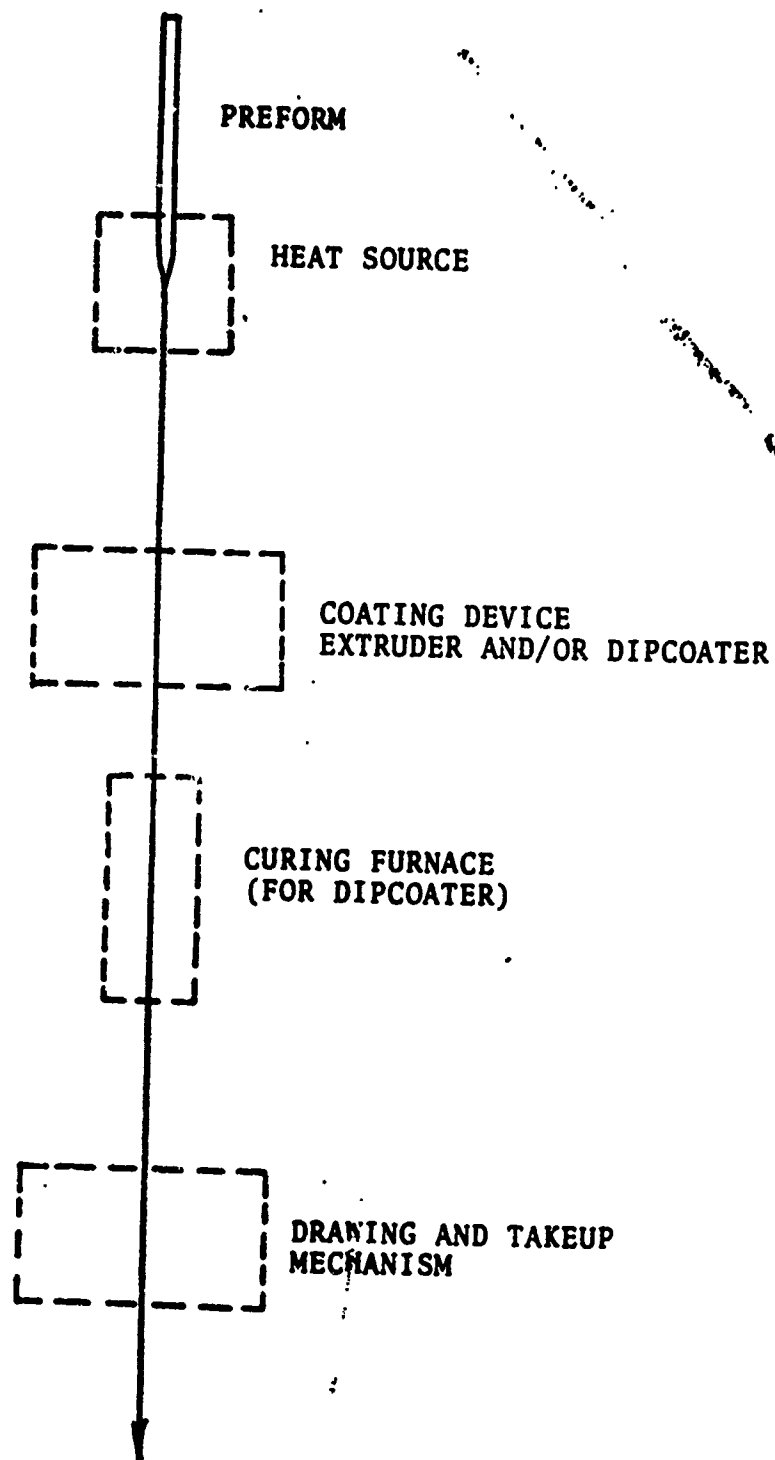


FIGURE 2-1
BASIC FIBER DRAWING SET-UP

molten plastic under high pressure into a crosshead through which the fiber is passed at a constant speed. At the exit point, plastic flowing through an annular orifice coats the fiber uniformly as it is pulled through the crosshead. Adequate distance between the extruder exit and the take-up mechanism is provided to allow the clad fiber to cool.

The extrusion process falls roughly into two categories, depending on the design of the die used within the crosshead. If the end of the guide terminates prior to the land of the die, plastic is forced against the fiber at the exit point and the diameter of the extrudate is approximately equal to that of the die. This process is termed "pressure extrusion." Alternatively, if the tip of the crosshead guide is positioned flush with the end of the die, the extrudate flows from the orifice in tubular form, making contact with the fiber at some distance from the crosshead. The latter process is referred to as "tubing-on." Parameters can be selected to vary the wall thickness and to vary the cladding from a close fit or bond to a tubing which loosely encapsulates the fiber.

The "tubing-on" process was most suitable for cladding optical fibers. In this case a plastic tube is drawn onto the fiber where it reaches a final diameter. The ratio between the cross sectional area of the die opening and that of the plastic cladding is termed the draw down ratio:

$$\text{Draw Down Ratio} = \frac{D^2 - T^2}{d^2 - f^2}$$

where

D = inside diameter of the die

T = outside diameter of the guide tip

d = Diameter of the clad fiber

f = Diameter of the fiber

This relation applies for both balanced and unbalanced draw down of the inner and outer surfaces of the plastic clad. In view of the thin wall required for optical fiber coatings, it is imperative that a near balanced draw down be used. Failing to achieve this condition can lead to extrudate cone breaks and melt fracture.

2.1.2 In-Line Dip Coating Technique

In-line dip coating of the fibers was accomplished by positioning a dip coater device between the heat source and the drawing take-up mechanism. The fiber immediately after drawing passes through the reservoir of the dip coater which contains the plastic solution or dispersion. At the bottom of the reservoir a wiping die removes excess plastic to maintain a uniform cladding thickness which is controlled by the opening of the wiping die, the fiber pull speed, the viscosity of the cladding material, and the as-drawn fiber diameter. Immediately following the dip coater, the fiber is pulled through a curing furnace to evaporate the solvent and to accelerate curing of the plastic.

To preserve the mechanical integrity of dip coated surfaces it was found necessary to overcoat the cladding layer with an additional protective layer. This technique not only protects the cladding from additional damage but also considerably eases fiber handling.

Two coating techniques have been employed during the course of the contract program. The first technique consists of dip coating the fiber in-line with the plastic cladding in one operation and extruding the protective coating during a second operation. This process requires the clad fiber to be spooled prior to application of the protective coating. The second technique consists of applying the cladding and protective coating in-line in one operation. Both techniques have resulted in high quality fibers, however, the latter technique exhibits potential for producing fibers at a lower cost.

2.2 Silica Core and Plastic Cladding Material Evaluation

To meet the objectives of optical attenuation and numerical aperture, mechanical integrity, and resistance to environmental attack and nuclear radiation, a number of silica core and plastic cladding materials were investigated. A detailed discussion of this effort is presented in the following sections.

2.2.1 Core Materials

The selection of suitable silica core materials was based on spectral attenuation characteristics, particularly in the wavelength range from 0.75 to 0.85 microns, resistance to nuclear radiation, availability, and cost. Whenever possible, published data were utilized to select a group of suitable candidates. For the case where published data were not available, material characteristics were determined by evaluating a variety of plastic-cladded silica core combinations.

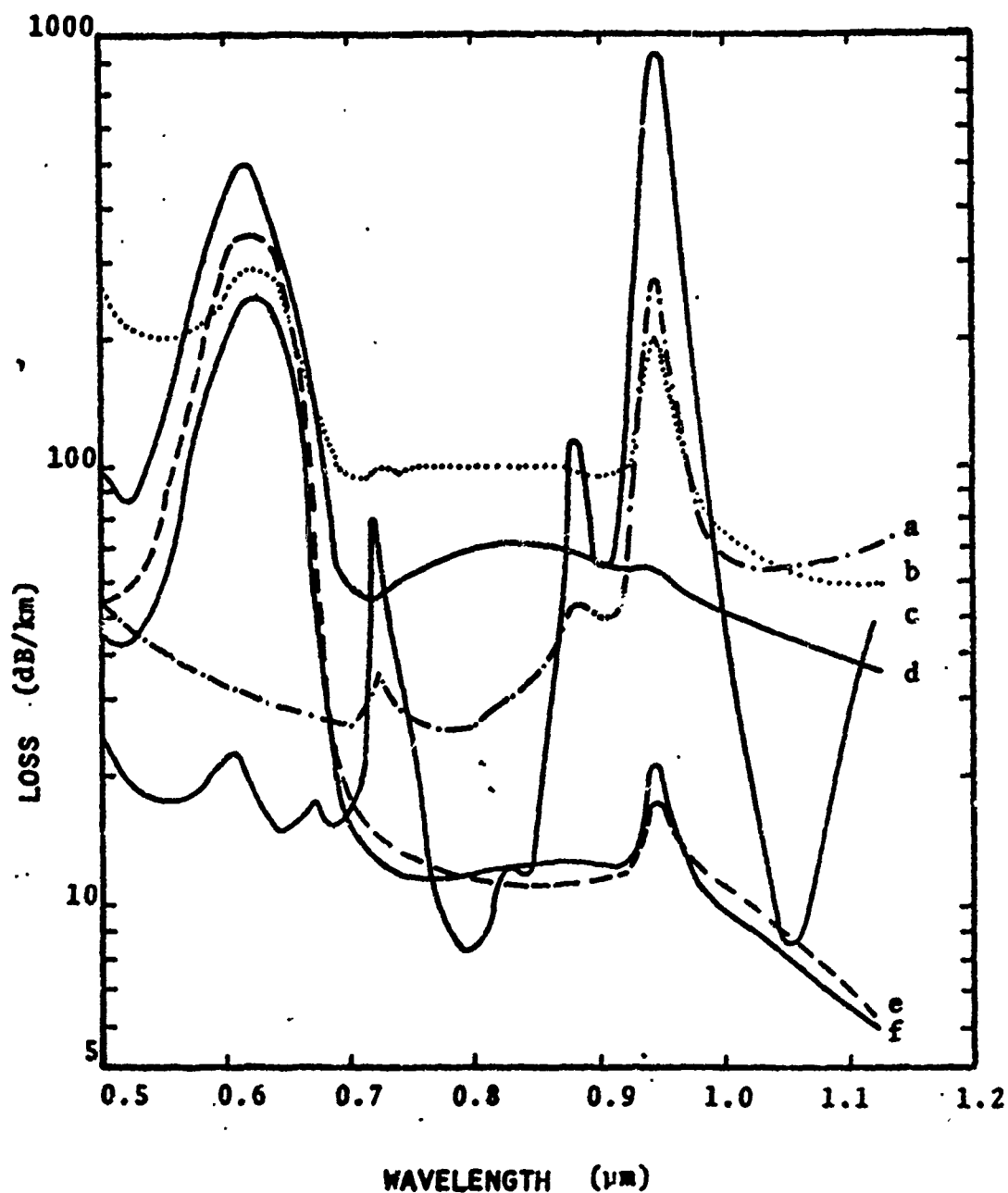
Commercial silicas fall into three classes - natural, moderate water content artificial, and low water content artificial. The pure natural silicas are obtained from pure mineral deposits and fabricated into convenient shapes for further processing using techniques designed to maintain their natural purity. The moderate water content silicas are produced by flame hydrolysis, while the low water content silicas are produced by water free reactions.

Silicas of each type are available under several trade names. Several are listed in Table 2.1.

Spectral loss curves have been published for fibers drawn from several of the commercially available silicas. Figure 2-2 shows published spectral loss curves of unclad fibers of T08, Suprasil 1, Suprasil W1 and Suprasil W2. All of these silicas can meet the attenuation requirement in the specified wavelength range. In addition to the above-listed silicas, Suprasil 2, Spectrosil

TABLE 2.1
COMMERCIAL SILICAS

Natural	Moderate Water Content Artificial	Low Water Content Artificial
T08	Suprasil 1	Suprasil W1
Homosil	Suprasil 2	Suprasil W2
Optosil	Spectrosil B	Spectrosil WF
	Silanox B	



- (a) commercial grade T08
- (b) Ultrasil
- (c) Suprasil 1
- (d) Infrasil
- (e) Suprasil W2
- (f) Suprasil W1

SPECTRAL LOSSES OF UNCLAD SILICA FIBERS¹

¹"Spectral Losses of Unclad Vitreous Silica and Soda-lime-Silicate Fibers," P. Kaiser, J.O.S.A., V.63, No.9, Sept. 1973.

FIGURE 2-2

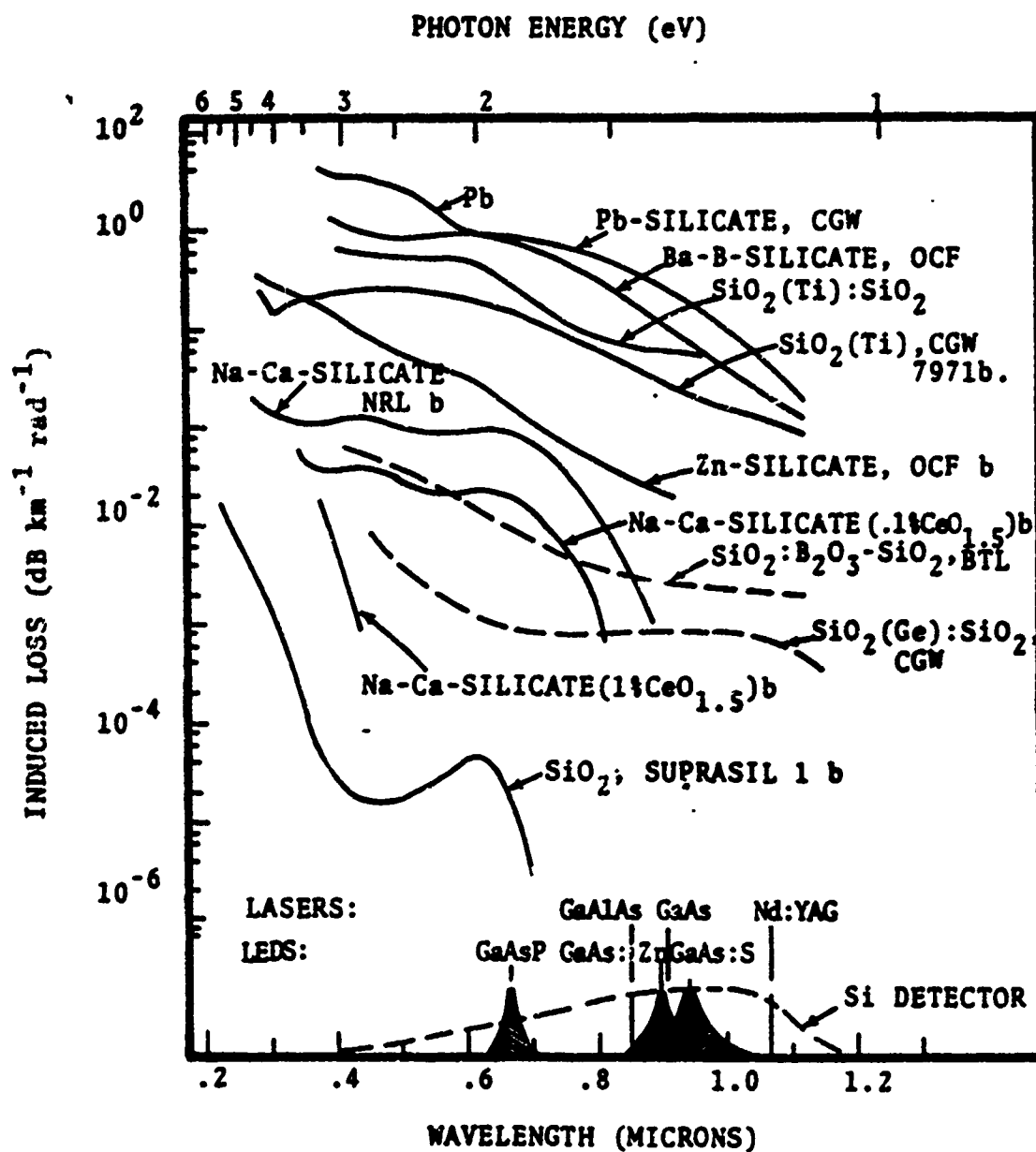
WF, Homosil, Silanox B and Optosil were evaluated for their attenuation characteristics by extruding or dip coating an optical cladding over as drawn fibers.

Figure 2-3 shows the radiation-induced changes in optical attenuation for a number of silicas. The curves show that Suprasil 1 exhibits minimum induced attenuation of all materials shown. Radiation induced loss measurements on EOPD produced plastic-clad silica fibers have been performed on final cable models and results are outlined in section 4.3.11.

Fiber cost was a key consideration for the program. Table 2.2 lists the cost per foot of fiber of all of the commercially available silicas. T08 has the lowest cost of all of the silicas investigated and it was used exclusively during early effort. However, the quality of preforms was found to vary. Since Suprasil 1 and the chemically similar Suprasil 2 offer lower attenuation and higher radiation resistance, and since their cost is consistent with expected processing costs, they were considered the prime candidates.

2.2.2 Selection of Plastic Optical Cladding Materials

The selection of plastic optical cladding materials was based on their optical properties, mechanical and environmental survivability, and suitability for various coating techniques. In addition, these materials were evaluated for their suitability as



RADIATION INDUCED CHANGES IN OPTICAL ATTENUATION²

²"Radiation Effect in Fiber Optic Waveguides," G.H. Sigel, Jr., NRL Memorandum Report 2934, NRL, Nov. 1974.

FIGURE 2-3

TABLE 2.2

SILICA MATERIAL COST
(125 μ m diameter)

<u>Material</u>	<u>Cents/Fiber Foot</u>
T08	.06
Suprasil 1	.91
Silanox A	6.55
Silanox B	2.25
Silanox WF	8.51
Suprasil W2	7.41
Spectrosil WF	7.49
Suprasil 2	.38

a protective coating to establish the requirement for an additional overcoat and to establish their suitability as a buffer layer to reduce microbending losses during cabling and bundling. Table 2.3 lists the prime plastic optical cladding materials evaluated during the first six months of the contract period. Shown in this table are the cost, application technique, index of refraction, water permeability, and operating temperature range. Several fluoropolymer suspension coatings were briefly examined and found to be unsatisfactory because of their high intrinsic attenuation.

2.2.2.1 Extruded Coatings

Teflon coatings offer a number of desirable properties. The high melting point allows the use of a large variety of cable jackets without the fear of melting the cladding or coating. The coating is tough and flexible, exhibits low coefficient of friction, and is chemically inert. PFA exhibits low water permeability and absorption.

FEP-100 and FEP-110 were initially extruded over T08 to establish optimum extrusion conditions. During the course of this investigation it was found that the presence of gel particles caused frequent cone breaks in the extrudate. In addition, melt fracture was observed when a thin coating of FEP 100 or FEP 110 was applied to the fibers as an optical cladding.

Melt fracture, which is caused by shear stresses, can roughen the inner and outer surface of the extrudate, and can give rise to scattering losses. Extrusion conditions must, therefore, be such

TABLE 2.3
CLADDING MATERIAL CHARACTERISTICS

<u>Material</u>	<u>Cost \$/lb.</u>	<u>Application Technique</u>	<u>Index of Refraction</u>	<u>Water Permeability</u>	<u>Temperature Range</u>
FEP 100	6.50	Extrusion	1.338	.40	-200 to 200
FEP 110	7.50	Extrusion	1.338	.40	-200 to 200
PFA 9704	9.00	Extrusion	1.334	*	-200 to 260
Silicone RTV	10.00	Dip Coat	1.39	*	* to 300

* to be determined

that reduced shear stresses are achieved in the extrudate, especially where the extruded plastic serves as the optical cladding. These conditions can usually be met with thin coatings by increasing the crosshead die opening and the die temperature and by increasing the melt temperature and extrusion throughput. Because of the present limitation in drawing speed, the above conditions could not be achieved with FEP 100 and FEP 110. Although FEP 100 was free from gel particles, process conditions with respect to melt fracture were more critical than with FEP 110.

To overcome these problems, Teflon PFA 9704 was evaluated. It exhibited good extrudability which allowed application of thin and thick cladding and multiple claddings. These claddings were applied without melt fracture and cone breaks by optimizing extrusion conditions. Because of its superior extrudability, in addition to meeting the optical characteristics required for a cladding material, Teflon PFA was considered a viable candidate for plastic-clad silica fiber fabrication.

Experiments on cladding thickness revealed that the optical quality of PFA claddings varied inversely with cladding thickness, requiring a draw down ratio from 900 to 2000:1. This extremely high draw down ratio lead to pin holes in the extrudate which are detrimental to the mechanical properties of the clad fiber and were found to cause an increase in attenuation when the fiber was immersed in boiling water for several hours. The high draw down ratio also lead to cone breaks when not all of the extrusion conditions are optimized. Further optimization of extrusion

parameters for PFA resulted in clad fibers which exhibited excellent mechanical and optical characteristics.

2.2.2.2 Dip Coatings

It was reported that extremely low optical attenuation can be achieved using a dip coating of silicone RTV. Other desirable properties of the silicone resins are (1) relatively uniform mechanical properties over wide temperature ranges, (2) high water repellency, and (3) chemical inertness. Thus, the use of silicone resin dip coating was investigated.

The cured flexibility of silicone RTV enhances the mechanical properties of the fibers and its cured consistency aids reduction of microbending effects. The viscosity of the silicone RTV resins used was found to be adequate for dip coating, allowing optical cladding thicknesses which could be readily coated with protective layers by extrusion using the same extruder dies and techniques used with the optical cladding application processes. The numerical aperture and associated index of refraction exhibited by silicone clad fibers were within the levels specified in the technical guidelines of the contract. These superior properties of silicone RTV resins exhibited over those of the Teflon plastics resulted in silicone RTV plastic-clad silica fibers ultimately being selected for the cable fabrication effort.

2.3 Fabrication and Evaluation of Plastic-Clad Silica Combinations

Based on the evaluation of material properties and application techniques for silica and plastic cladding materials, a number of plastic clad silica combinations were experimentally evaluated with respect to fiber attenuation, mechanical strength and numerical aperture. In addition, the use of multiple coatings to reduce micro-bending losses was also investigated.

Table 2.4 lists plastic-clad silica combinations which were investigated in detail during the first six months of the contract program.

2.3.1 Optical Evaluation of Plastic-Clad Silica Combinations

The optical evaluation of clad fibers included coating the fibers with thick and thin claddings, multiple claddings of the same material and with dissimilar materials, and then measuring attenuation between 0.6 and 1.06 micron wavelengths. The objective of this effort was to achieve minimum loss and to reduce microbend induced losses. The optical characteristics of these combinations were determined by employing the measurement technique described in Appendix A.

During the fabrication process, fibers were wound on drums or spools or collected in loose coils. The attenuation of fibers varied over a wide range, when wound on spools and drums or in coiled form. Usually the highest values were obtained for spooled fibers. Excess losses may be introduced due to the cross-over of fibers in the spooled condition.

TABLE 2.4
PLASTIC-CLAD SILICA COMBINATIONS

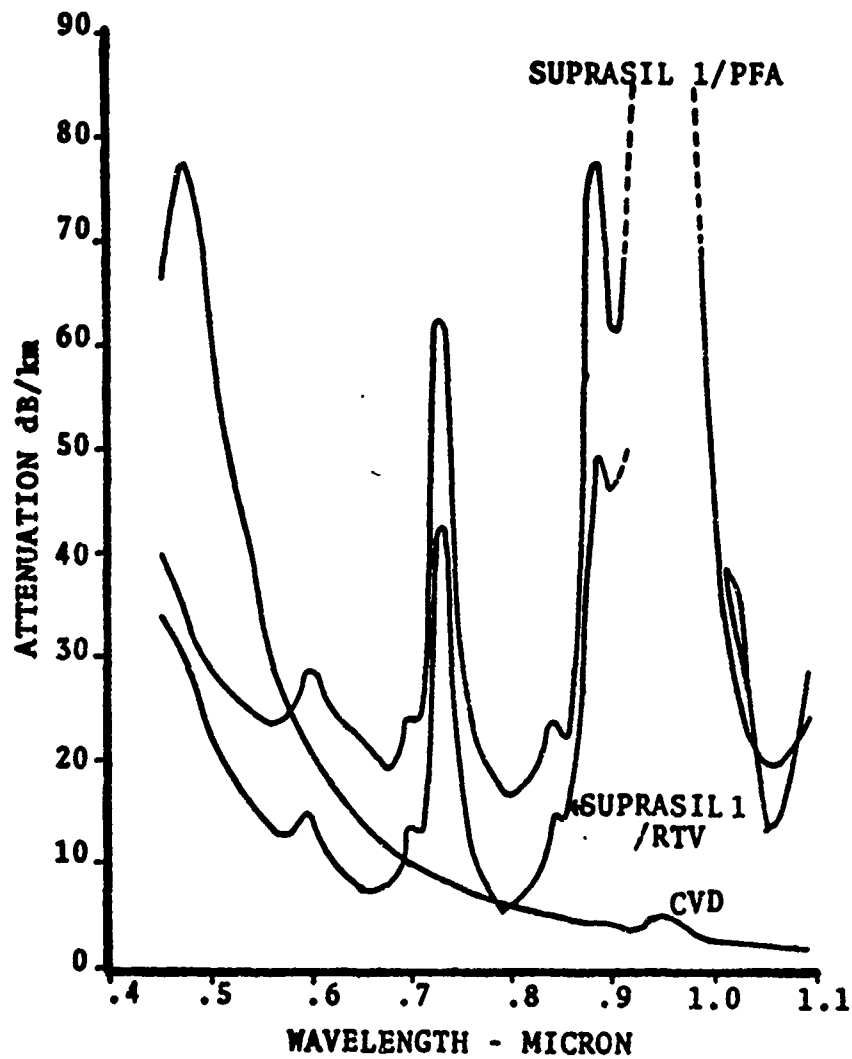
<u>Silica</u>	<u>Optical Cladding</u>	<u>Outer Jacket</u>	<u>Fabrication Process</u>	<u>Loss (dB/km) 0.79μ</u>
TOS	FEP-110		Extrusion	*
TOS	FEP-100		Extrusion	*
TOS	PFA		Extrusion	30.7
Suprasil 1	PFA		Extrusion	17.0
Suprasil 1	PFA	PFA	Double Extrusion	31.5
Spectrosil WF	PFA		Extrusion	22.3
Silanox B	PFA		Extrusion	6.6
Suprasil 1	Silicone RTV **		Dip Coat	5.5
Suprasil 1	Silicone RTV **	PFA	Dip Coat & Extrusion	8.3

*Excess loss due to vendor problems with TOS optical quality

** Dow-Corning Sylgard^R

To eliminate the effects of microbend-induced losses as described above, the loss characteristics of plastic-clad silica fibers listed in Table 2.4 were measured when the fibers were strung between large diameter drums. The results given were the best obtained. The results of the most attractive combinations - silicone resin and PFA coated Suprasil 1 - are plotted as complete spectral loss curves in Figure 2-4. Also shown for comparison is a curve for a doped silica fiber produced at EOPD.

Various experiments were performed to determine the best approach to excess loss reduction. Double claddings of PFA and thick and thin coatings of PFA on silica fibers were evaluated with respect to microbending induced losses. The effect of cladding thickness was studied by applying claddings of various thickness of PFA on Suprasil 1 fibers. Thin claddings exhibited less cladding-scattering losses but were more susceptible to microbending effects. Thick claddings exhibited higher scattering losses but reduced microbending losses. These results lead to an investigation of double cladding to incorporate the thin cladding for scattering loss reduction and the thick cladding for microbending loss reduction. Loss reduction utilizing double PFA cladding was limited because the application of the hot second PFA coating over the thin PFA optical cladding severely affected its optical properties, especially with thick second coatings. Furthermore, results tended to be inconsistent.



SPECTRAL ATTENUATION OF CVD AND PLASTIC CLAD SILICA FIBERS

FIGURE 2-4

The silicone RTV coated fibers were measured both spooled and strung to evaluate the microbending effects with the cladding. The combination of silicone RTV and Suprasil 1 exhibited little loss increase when spooled, especially for the lower loss strung fibers, which indicated that silicone resin claddings have excellent mechanical properties with respect to excess loss prevention. However, the silicone RTV cladding was susceptible to abrasion damage and was therefore coated with PFA as a protective jacket. Again, a high resistance to excess loss was observed comparing spooled and strung attenuation results. Measurement of a number of fibers indicated a difference of 3-5 dB/km between spooled (4" diameter spool) and strung fibers.

The silicone resin fibers, which have lower attenuation and higher resistance to excess loss than the PFA cladded fibers, also exhibited a higher numerical aperture. Figure 2-5 shows the relative insertion loss as a function of numerical aperture for a random selection of 6 silicone resin cladded fibers and 6 PFA cladded fibers. The 1 dB point, which is a useful definition of numerical aperture, is .30 for the silicone resin cladded fibers and .19 for the PFA cladded fibers. The plotted lines indicate average values of the points at .24 and .33 NA. The discrepancy between the calculated NA of .55 (page 2-2) and the measured NA of approximately .19 is felt to be a result of scattering of higher order modes by the cladding and by the irregular core-cladding interface formed by PFA.

During the last half of the program, additional experiments were conducted with a number of prospective silicone RTV cladding

materials. Silica coated with Shin-Etsu was found to exhibit lower attenuation than when coated with the Dow-Corning material (<10 dB/km at $.79\mu$). Processing techniques for all silicone RTV materials were in accordance with the manufacturers' data sheets.

LOSS VERSUS NUMERICAL APERTURE

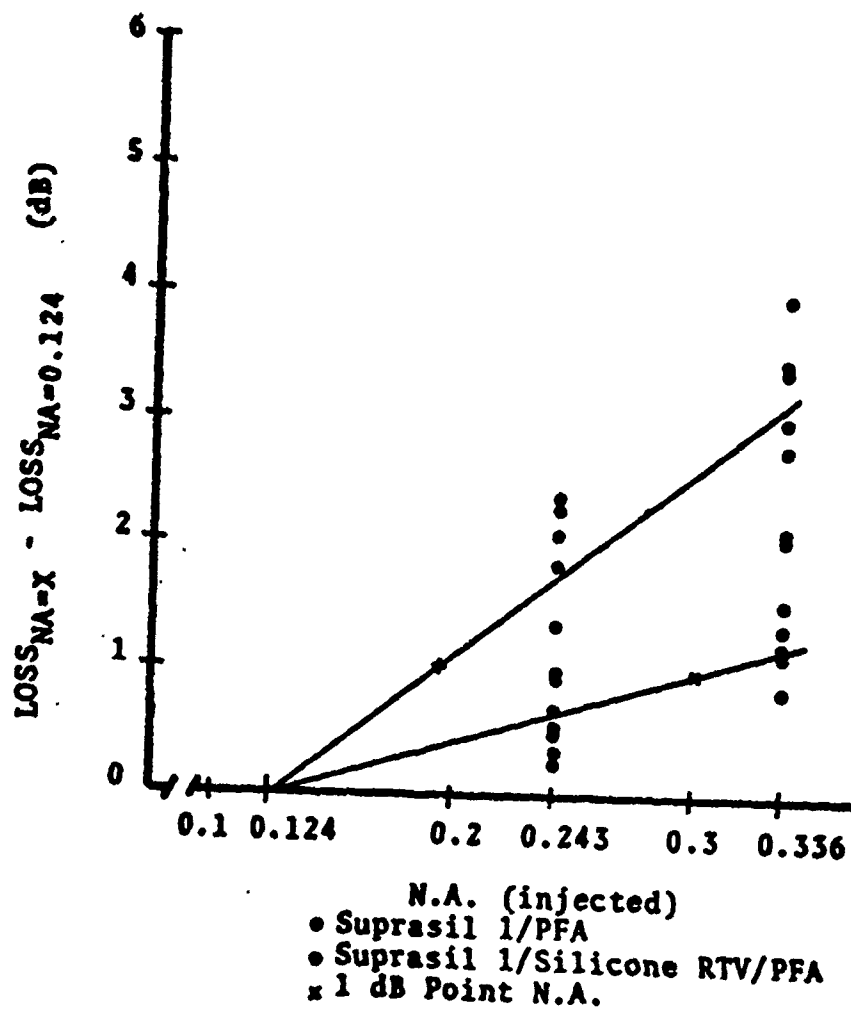


FIGURE 2-5

2.3.2 Mechanical Evaluation

The strength of optical fibers is of great importance since maximum yield in the cabling process and long life in the field are desirable. Early in the low cost cable development program it became apparent that silicone resin cladded fibers exhibited strengths greater than fibers that had been extrusion-cladded. Average tensile strengths exceeded 300,000 psi and minimum strengths rarely measured below 100,000 psi. Further development of fiber coating techniques during the last half of the contract period resulted in average fiber strengths that exceeded 1,000,000 psi in 60 cm gauge lengths.

2.3.3 Effects of Moisture and Temperature on Fiber Attenuation

To determine the effects of moisture and temperature on attenuation the core-cladding combinations fabricated with PFA and silicone RTV were submersed in boiling water for two hours. The PFA cladded fiber exhibited an increase of approximately 50 dB/km whereas the silicone RTV cladded fiber exhibited no measurable increase. To establish which factor (the temperature exposure or water penetration) caused the observed attenuation increase, two samples of fibers were exposed to 100°C for one hour in the absence of water. Neither cladded combination exhibited an increase in attenuation. This indicated that water penetration of the PFA cladded fiber caused the increase in attenuation.

2.3.4 Conclusion

Silicone resin clad Suprasil 1 and Suprasil 2 fibers with PFA jackets were chosen for cable fabrication because of their low attenuation, high numerical aperture, high strength, potential of high radiation resistance, high moisture resistance, consistency of results, and small tendency to exhibit excess loss.

3.0 CABLE DESIGN

Objectives for the cable design included low excess attenuation, high tensile strength, high flexibility, small bend radius, low electrical conductivity, and EMI/EMP immunity. This section describes design approaches and material selections made to best meet the program objectives. Included are discussions of strength member material selection, cable structure and jacket and filler materials.

3.1 Strength Member Materials

In general, for compact cables, it is expected that strength member strain will roughly equal fiber strain. Thus if it is assumed that the strength members will carry almost the whole load - a conservative estimate - it is desirable that the strength members have the highest stress possible at .01 strain. Investigation of commercially available non-metallic strength member materials showed that Kevlar^R 29, Kevlar^R 49 and carbon yarns could best meet this objective.

It should be noted that carbon fibers have the draw back that they are slightly conductive. Stress-strain curves for these materials are shown in Figure 3-1 along with one for bulk silica for comparison.

Kevlar^R is a high modulus material. It has been obtained as a multifilament yarn which is coated to reduce friction between individual filaments.

Investigation of carbon and graphite yarns revealed a tensile strength lower than manufacturer's reported values for yarns which were incorporated in a matrix which allowed adequate smoothness and flexibility. Initial bundling attempts resulted in breakage of individual filaments of the yarns due to a "sticky" property of the material causing kinking of the filaments. The tensile strength measurements made at EOPD on these carbon yarns yielded values no higher than those observed for the less expensive Kevlar^R yarns. Another commercially available carbon fiber yarn which was encapsulated in an epoxy vehicle exhibited flexibility unsuitable for fiber optic cables due to its stiffness. Work is presently under way to develop a carbon yarn in a new type of vehicle which will allow adequate flexibility and smoothness and exhibit tensile strength greater than those of Kevlar^R yarns. However, the results of this effort will not be available in time for the present program.

STRESS vs STRAIN FOR APPLICABLE STRENGTH MEMBER MATERIAL

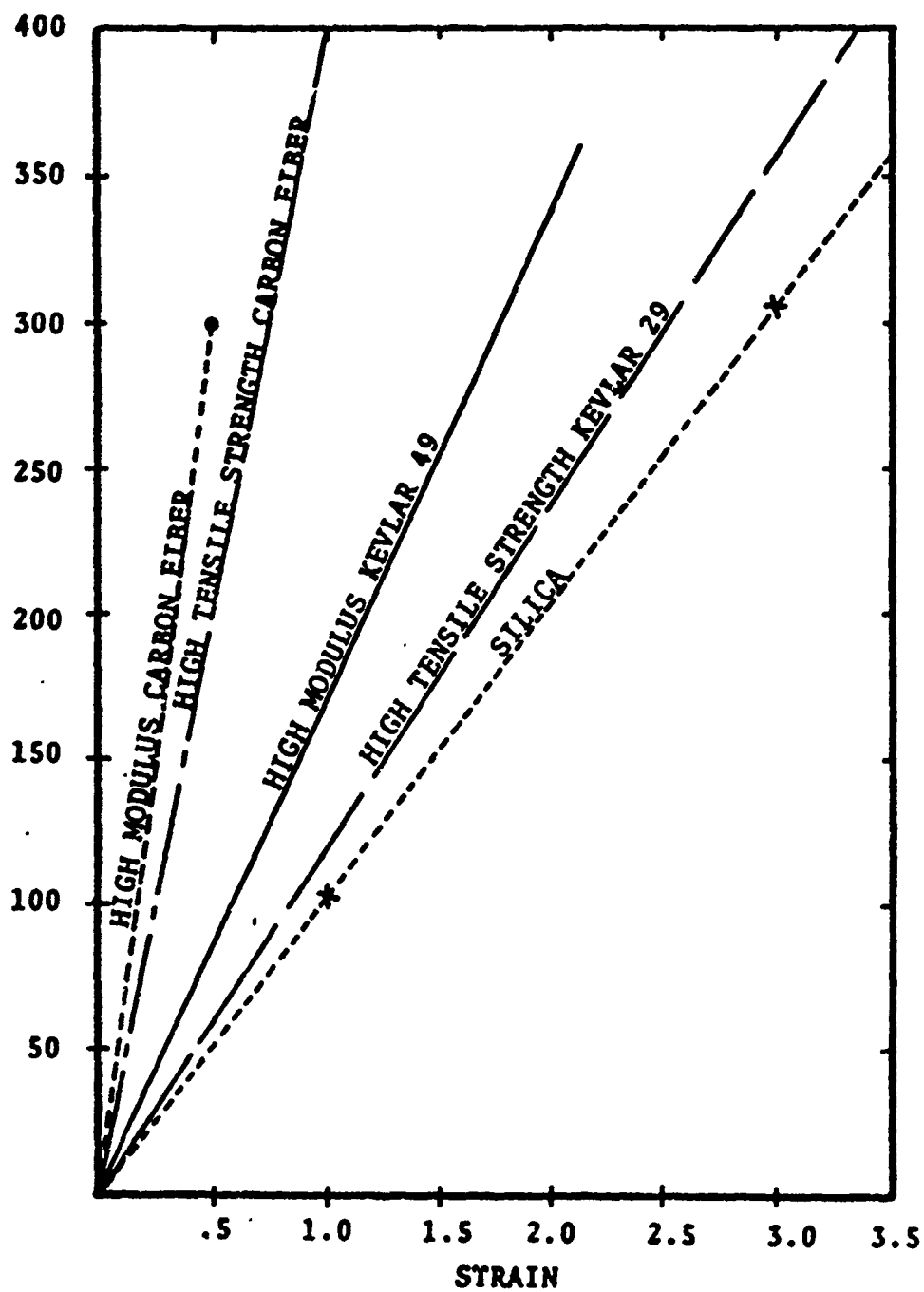


FIGURE 3-1

3.2 Cable Designs

Initial effort resulted in the development of three designs for preliminary evaluation, one with central strength members and a single layer jacket, one with central strength members and a three layer jacket, and one with external strength members. These designs, though intended for plastic clad silica fibers in the present effort, should also be applicable to doped silica and other low loss design.

3.2.1 Central Strength Member-Single Layer Jacket Design

Under contract with the Navy Electronic Center, ITT developed the central strength member cable for low loss optical fibers shown in Figure 3-2. This design served as a starting point for the central strength member cable design to be developed under this contract.

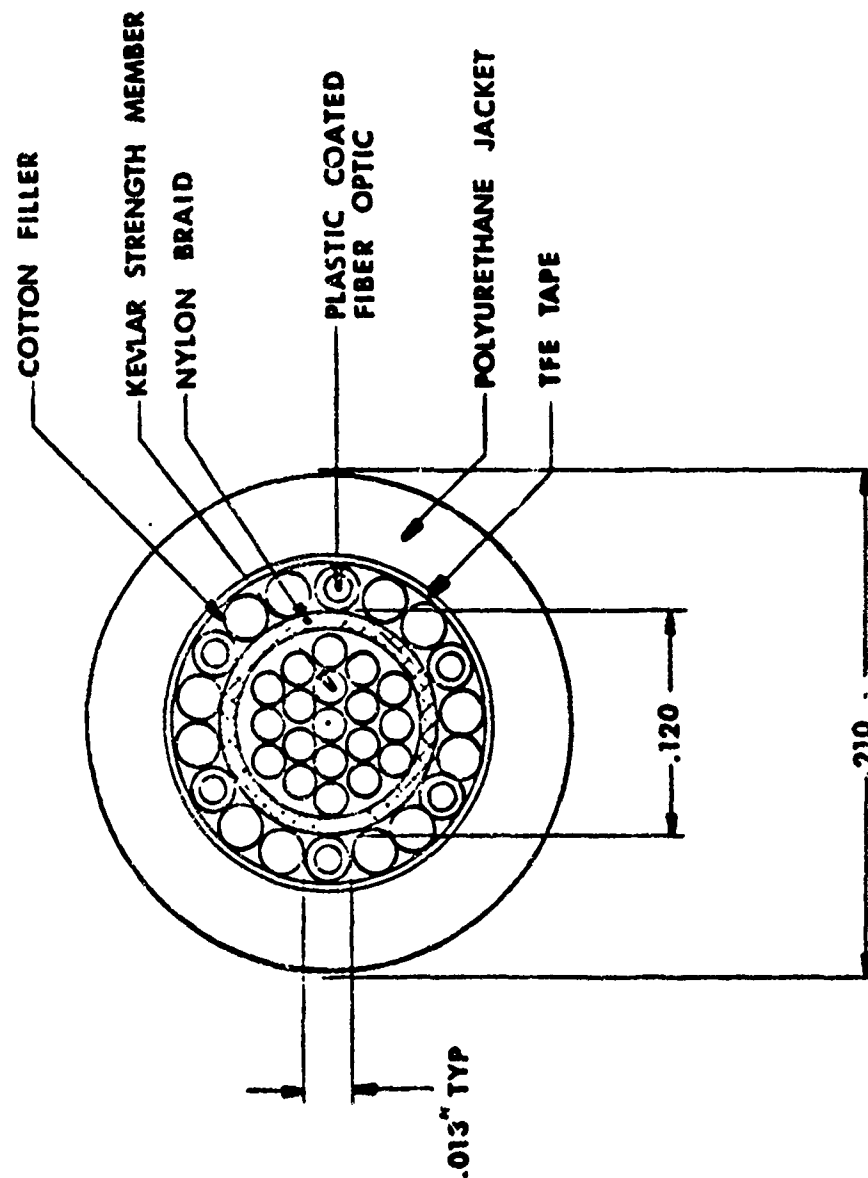
The NELC central strength member design employed 19 strands of Kevlar^R 49 (1420 deniers) impregnated with polyurethane. The strength member was contained in a Nylon braid to provide a smooth surface for excess cable loss reduction. Six optical fibers and 12 cotton fillers were helically stranded around the strength member with a 4 inch lay. The fibers and fillers were wrapped with an uncured Teflon TFE tape. The outer jacket is an extruded polyether base polyurethane material. The tape serves to reduce friction between the fiber layer and the outer polyurethane jacket.

Cable samples from the earlier program were subjected to MIL-C-13777F

DESIGN

RESULTS

DELIVERED CABLE 4 x 400 METERS
 LOWEST ATTENUATION 8 dB/km
 NUMERICAL APERTURE > .25
 TENSILE STRENGTH 500 lb.
 (5 meter gage length)
 MIN. BEND RADIUS $\approx 3/4"$



NELC CABLE

FIGURE 3-2

tests. Tests performed included impact, bend and twist. Results were as follows:

a) Impact Test - Per MIL C 13777F at room temperature.

Requirements - 200 cycles for cables less than 1/2 inch in diameter using a 10 lb weight with a 6 inch drop.

<u>Results</u>	<u>Fibers - Cycles to Failure</u>					
Sample No.	1	2	3	4	5	6
1	0	10	30	60	75	80
2	1	1	36	62	71	71
3	1	1	59	58	78	105
4	3	22	72	83	81	87
5	0	2	72	79	79	80
6	1	1	17	26	47	73
* 7	57	209	7650	7650	7650	7650

Note: 0 cycle - fiber not transmitting light initially

* #7 sample tested using 5 lb weight and 6 inch drop

b) Bend Test - Per MIL C 13777F at room temperature

Requirements - 2000 cycles, 20 lb weight, and 180° bend

<u>Results</u>	<u>Fibers - Cycles to Failure</u>					
Sample #	1	2	3	4	5	6
1	0	20	>2500	>2500	>2500	>2500

c) Twist Test - Per MIL C 13777F at room temperature

Requirements - same as for the Bend Test

<u>Results</u>	<u>Fibers - Cycles to Failure</u>					
Sample #	1	2	3	4	5	6
1	0	>2500	>2500	>2500	>2500	>2500

Failure of some fibers to transmit at the start of the tests was due to a set up problem which has been identified and corrected.

Two tests - tensile and high temperature - on the cable performed under the previous Navy program are also of interest here.

Tensile strength tests were performed on seven cable specimens, six of which were 20 meters long and one 5 meters. A load was applied to the samples in 50 pound increments with the elongation being measured at each step. The first fiber break occurred between 200 and 450 pounds for the 20 meter samples, the average being about 300 pounds. The first fiber break occurred at 0.8% elongation. Average elongation at 500 pounds tension was 1.25% for cables with a straight strength member. The 5 meter section of the cable with a straight strength member was stressed to 500 pounds and 1.2% elongation with no fiber breakage.

The high temperature test consisted of elevating the temperature for one week to 65°C. At the completion of the test and subsequent cable transportation it was found that all fibers failed to transmit. The source of the failure was traced to shrinkage of the Nylon braid and fusing of the polyurethane impregnated strength member strands which caused the cable to become rigid and led to fiber breakage when the cable was bent.

Evaluation of the test results described above led to the conclusion that the basic design was sound, but that some modification of the strength member design would be necessary.

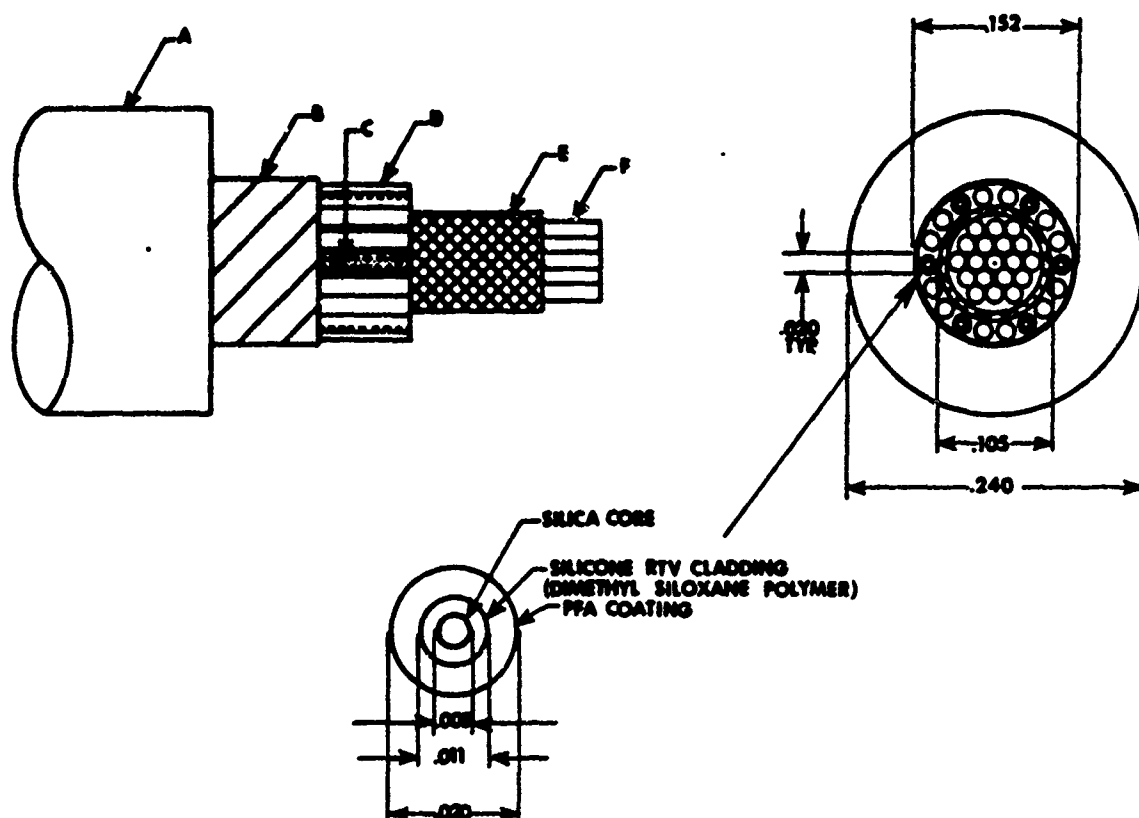
As a result, the following modifications were made in the strength member:

- 1) Kevlar^R 29 was substituted for Nylon as the braid material to reduce braid shrinkage.
- 2) The polyurethane coated Kevlar^R 49 strength member strands were coated with silicone oil to inhibit fusing.
- 3) The strength member is prestressed to 400 lbs to reduce initial elongation when the final cable is loaded. In preliminary tests, exposure to 105°C for one week did not cause fusion of strength member strands.

Figure 3-3 shows the design for preliminary fabrication. The cotton fillers have been replaced by fungus resistant polyester yarn.

3.2.2 Central Strength Member - Three Layer Jacket Design

The central strength member three layer cable design shown in Figure 3-4 incorporates the same fiber bundle as used in the single layer cable. However, the polyurethane jacket which is extruded over the bundle is of reduced thickness to allow for the application of a pre-stretched Nylon braid and the outer polyurethane jacket, the objective being to maintain maximum diameter of .250". The single layer and three layer cables have similar outer diameters and were expected to exhibit the same tensile strength. The three layer cable design was expected to exhibit increased radial crush resistance due to the incorporation of the Nylon braid.



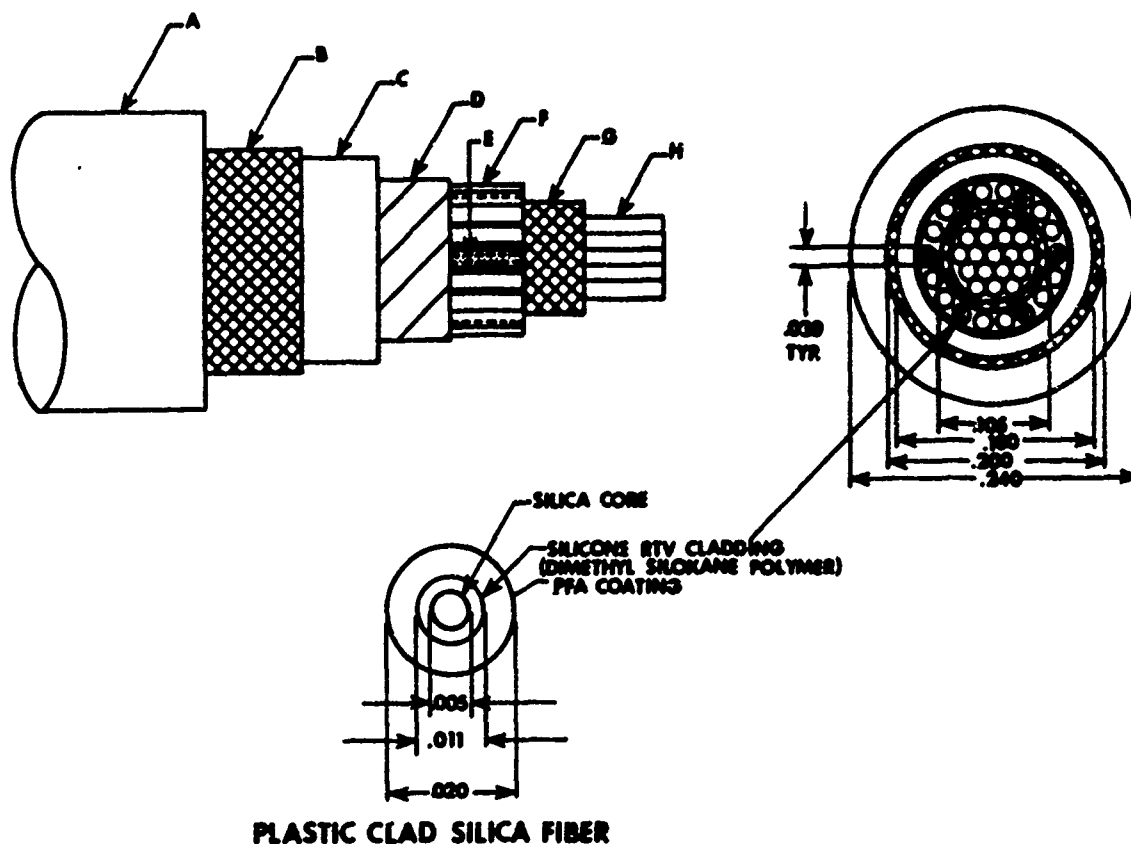
PLASTIC CLAD SILICA FIBER

- A. Polyether Type Polyurethane Jacket, .240" Dia.
- B. Tape, Uncured PTFE, .003" Thick x .375" Wide, 14% Overlap, 55° Wrap Angle
- C. 6 Plastic Clad Silica Fibers, .020" Dia. Each, Lay Length 4.2"
- D. 12 Polyester Yarn Fillers, .020" Dia. Each, Lay Length 4.2"
- E. Braid, Kevlar[®]-29, 400 Deniers, 1 end, 14.5 Picks/Inch, 24 Carriers, 20° Angle
- F. Strength Member, 19 Kevlar[®]-49 Yarns, 1420 Deniers, Polyurethane Impregnated, Each Yarn .017" Dia., One Yarn At Center

	<u>Inner Layer</u>	<u>Outer Layer</u>
Lay Length	1.24"	2.42"
Lay Angle	5°	5°
No. Yarns	6	12

CENTRAL STRENGTH MEMBER-SINGLE LAYER DESIGN

Figure 3-3



- A. Polyether Type Polyurethane Jacket, . 240" Dia.
- B. Preshrunk Nylon Braid, .200" Dia., 2 Ends, 16 Carriers, 14 Picks/Inch, 57° Angle, 840 Denier Nylon[®]-66 Yarn
- C. Inner Polyether Type Polyurethane Jacket, .180" Dia.
- D. Tape, Uncured PTFE, .003" Thick x .375" Wide, 14% Overlap, 55° Wrap Angle
- E. 6 Plastic Clad Silica Fibers, .020" Dia. Each, Lay Length 4.2"
- F. 12 Polyester Yarn Fillers, . 020" Dia. Each, Lay Length 4.2"
- G. Braid, Kevlar[®]-29, 400 Deniers, 1 End, 14.5 Picks/Inch, 24 Carriers, 20° Angle
- H. Strength Member, 19 Kevlar[®]-49 Yarns, 1420 Deniers, Polyurethane Impregnated, Each Yarn .017" Dia., One Yarn At Center

	<u>Inner Layer</u>	<u>Outer Layer</u>
Lay Length	1.24"	2.42"
Lay Angle	5°	5°
No. Yarns	6	12

CENTRAL STRENGTH MEMBER-THREE LAYER DESIGN

Figure 3-4

3.2.3 External Strength Member Design

In earlier Army efforts the design of Figure 3-5 was developed. With this approach the strength member material, which is straight laid, causes the fibers to go into compression if the cable is bent in the plane of the strength members.

Figure 3-6 shows the external strength member cable design. The cable includes a central core of seven (7) close packed fibers in a polyurethane jacket to form a central core. Nineteen (19) Kevlar^R 49 strength members, which are helically laid around the central core, are covered with a Teflon TFE tape. The cable is enclosed in a polyurethane jacket. The longer lay length of the strength member is intended to reduce fiber tensile loading. The tape assures that strength members will not fuse to the jacket and thus allows the cable to bend freely in all directions.

3.3 Material Selections

In order to meet objectives of flexibility, crush resistance, and protection against chemical and radiation attack, several jacketing materials were evaluated. Polyurethane was selected as the jacketing material on the basis of its resiliency at low temperatures, abrasion resistance, and its chemical and environmental inertness. Polyurethane exhibits excellent extrudability and flexibility.

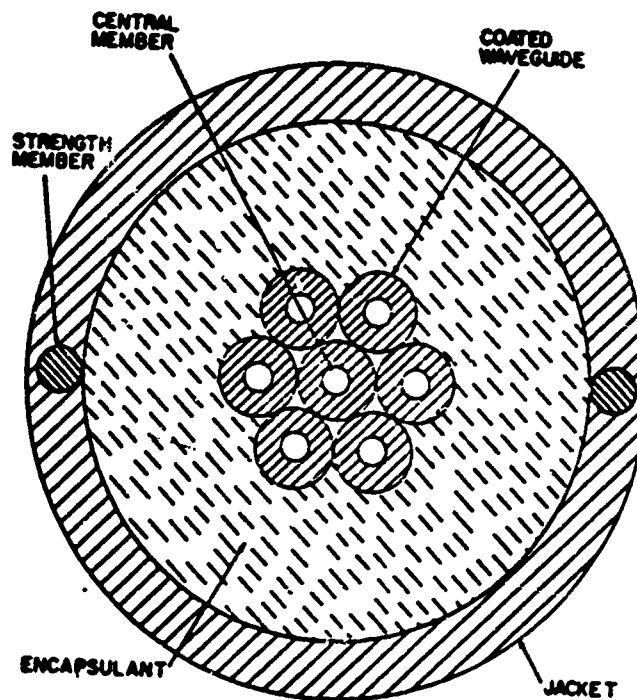
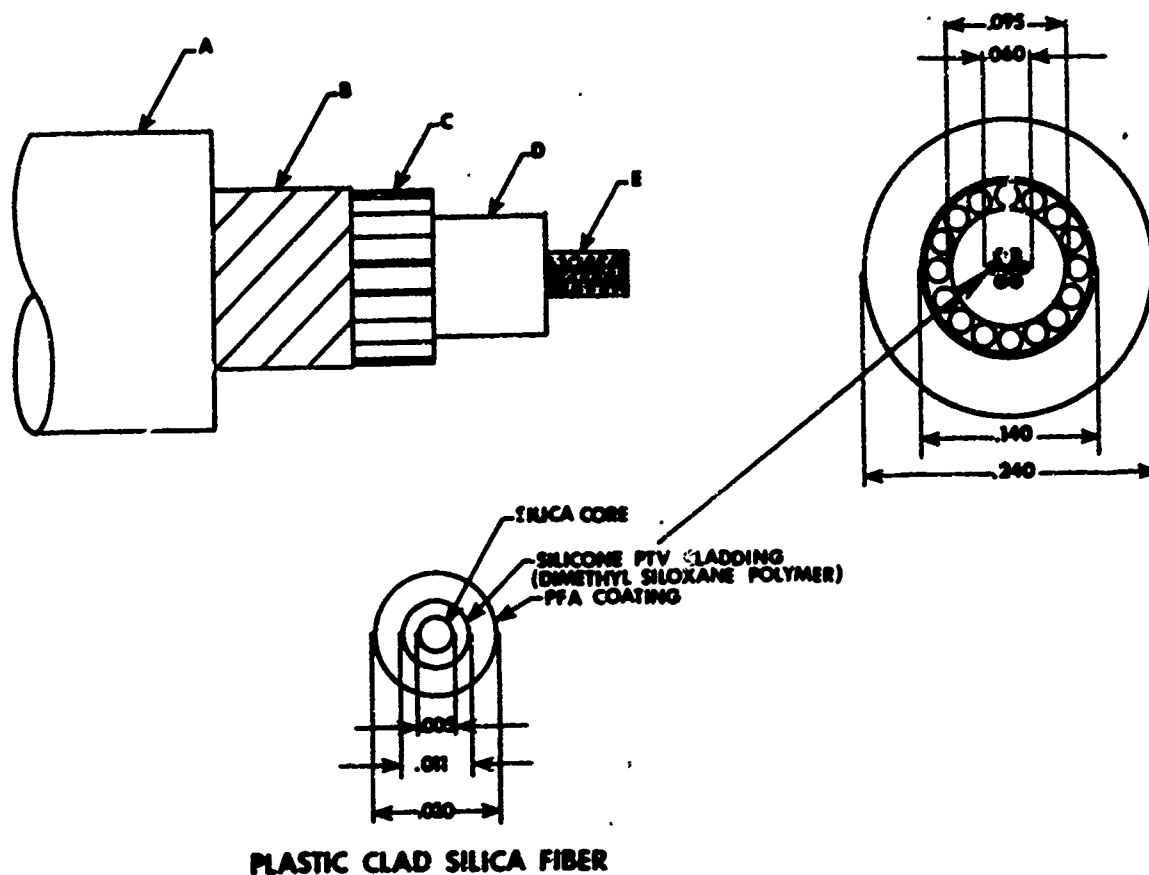


FIGURE 3-5



- A. Polyether Type Polyurethane Outer Jacket, .240" Dia.
- B. Tape, Uncured PTFE, .003" Thick x .375" Wide, 14% Overlap, 55° Wrap Angle
- C. 18 Aramid Yarns, Kevlar®-49, 1420 Deniers, Polyurethane Impregnated, Each Yarn .017" Dia.
- D. Polyether Type Polyurethane Inner Jacket, .095" Dia.
- E. 7 Plastic Clad Silica Fibers, .020" Dia. Each, Lay Length 2.0"

EXTERNAL STRENGTH MEMBER DESIGN

Figure 3-6

Uncured TFE tape was selected as an intermediate layer between the strength member or fiber bundle and the extruded polyurethane jacket to facilitate "sliding" between the components for increased cable flexibility.

For the cable design employing fillers, fungus resistant polyester fibers were used in place of Nylon.

4.0 CABLE FABRICATION

The first half of the cable development program entailed the development of suitable plastic-clad silica fibers and the formulation of cable designs that would provide adequate mechanical and environmental protection for the fibers. The second half of the program consisted of the fabrication and evaluation of the cables discussed in Section 3.0. This section will provide the results of evaluations performed on each cable design and will compare those results to program goals. Conclusions and recommendations for further study will be offered.

In the interest of easily identifying the individual cable designs discussed in section 3.0, descriptive nomenclatures were assigned as shown in table 4.1. The cables were fabricated in three phases:

- 1) Fabrication of short evaluation lengths (145-179 meters) of ECOM-1, ECOM-2, and ECOM-3 for ECOM's review and approval.
- 2) Fabrication of preliminary models consisting of two 1/3 km lengths of each of the three designs.
- 3) Fabrication of final cable models consisting of ECOM-1, ECOM-3, and ECOM-1A. The ECOM-2 design was eliminated for final model fabrication since it was a more costly cable design, yet offered no mechanical or environmental advantages over the ECOM-1 design. The ECOM-1A design was added as a variation of the ECOM-1 design and employed Mylar^R instead of Teflon^R tape.

TABLE 4.1

Cable Nomenclature

<u>Nomenclature</u>	<u>Description</u>
ECOM-1	Central Strength Member, Single Layer Design
ECOM-2	Central Strength Member, Three Layer Design
ECOM-3	External Strength Member
ECOM-1A*	Central Strength Member, Single Layer Design

*Similar in construction to ECOM-1 except employing Mylar^R tape instead of Teflon^R.

4.1 Fabrication of Evaluation Lengths

Prior to selection of cable designs for preliminary model fabrication, one short test length of each of the three designs was fabricated. Attenuation of the fibers was measured while on four inch diameter spools and again in the cables. Both measurements were made at a wavelength of .79 microns as shown in Table 4.2 and were intended to provide a rough indication of losses included in the fiber during the cabling process. It should be noted, however, that losses reported on fibers on four inch spools do include some microbend losses induced during spooling. In general, the results shown in Table 4.2 indicate that cabled plastic clad silica fibers can not only meet the required program goal of 50 dB/km, but can also meet the desired goal of 20 dB/km.

The three sample cables were submitted to ECOM for design evaluation and all three designs were subsequently selected for fabrication into 1/3 km preliminary models.

4.2 Preliminary and Final Model Fabrication

Fabrication of low cost cables for optical, mechanical and environmental evaluation was accomplished in two phases. In the first phase, preliminary models were fabricated in 1/3 km lengths and subjected to the following evaluations:

- 1) Attenuation measurement
- 2) Impact testing
- 3) Bend testing
- 4) Twist testing
- 5) Tensile loading
- 6) Moisture resistance
- 7) Temperature cycling

TABLE 4.2

CABLE ATTENUATION - dB/km
(.79 μ m .12 Injection N.A)

<u>Cable Type</u>	<u>Fiber Loss Before Cabling On Spool*</u>	<u>Fiber Loss After Cabling</u>	<u>Cable Length</u>	<u>Cable Diameter</u>
Central Strength Member, Single Layer	12.3 14.3 14.3 17.5 20.3 20.3 avg 16.5	8.8 12.7 15.3 19.5 24.9 25.8 avg 17.8	145 M	0.235 in.
Central Strength Member, Three Layer Design	12.3 14.3 14.3 17.5 20.3 20.3 avg 16.5	12.3 14.0 16.6 21.3 31.0 36.9 avg 22.0	145 M	0.250 0.270 in.
External Strength Member	12.0 12.0 12.0 12.0 16.0 20.3 20.7 avg 15.0	8.7 10.3 10.8 11.2 12.0 15.5 17.4 avg 12.3	179 M	.230 in.

* Spool diameter: 4.0"

The purpose of the evaluation was to determine the ability of the three cable designs to meet original program objectives and, in addition, to gain experience in evaluating optical cables using conventional cable testing techniques.

Final cable models were fabricated in longer lengths as follows:

<u>Cable Type</u>	<u>Length</u>
ECOM-3	1140 meters
ECOM-1	1020 meters
ECOM-3	520 meters
ECOM-3	336 meters
ECOM-1	317 meters
ECOM-1A	506 meters

Complete optical, mechanical, and environmental evaluations were conducted that included:

<u>Evaluation</u>	<u>Cable Model</u>
Attenuation	1, 3, 1A
Numerical Aperture	1, 3, 1A
Dispersion	1, 3, 1A
Tensile Load	1A
Impact	1A
Twist	1A
Bend	1A
Vibration	1, 3, 1A
Temperature Cycling	1A
Moisture Resistance	1, 3, 1A
Fungus	1, 3, 1A
Nuclear Survivability	1, 3, 1A

The following sections describe the testing and report the results. Conclusions and recommendations for further effort will also be offered. Reference is made to the Cable Test Plan, Appendix A,

The test plan describes the test, the test equipment, method of reducing and reporting data, and the test facility and personnel.

4.3 Attenuation and Dispersion

Attenuation and dispersion were measured in both preliminary and final cable models. Attenuation was measured at .65, .79, .82, and 1.05 microns with an injection numerical aperture of .124. Dispersion on the highest and lowest loss fiber in each cable was measured at the 3 dB and 10 dB points. Table 4.3 provides a general overview of the accomplishments of the program, comparing preliminary to final model average attenuation at .79 microns. Additional details regarding individual fiber attenuation for final cable models are shown in Table 4.4. Four-point spectral attenuation and dispersion plots are shown in Appendix B.

4.4 Impact Testing

Preliminary cable models ECOM-1, ECOM-2, ECOM-3, and final cable model ECOM-1A were impact tested in accordance with MIL-C-13777F (paragraph 4.5.4.1) and the Cable Test Plan shown in Appendix A. Earlier experience gained in impact testing the lightweight cable developed for NELC (Figure 3-2) indicated that fiber optic cables of that general size and design would not be capable of withstanding the full 200 impacts at 5 ft-lbs. In addition, previous cables that employed all-glass fibers developed under an ECOM contract (Figure 3-5) proved capable of withstanding 200 impacts at 1 ft-lb. One of the goals of the ITT program was to develop a low cost cable with improved impact resistance, but

TABLE 4-3

ATTENUATION

PRELIMINARY AND FINAL MODELS

CABLE TYPE	LENGTHS (Meters)	AVERAGE ATTENUATION @ 0.79μ	
		PRELIMINARY MODELS (dB/km)	FINAL MODELS (dB/km)
ECOM-1	354	20.0	-
ECOM-1	402	17.7	-
ECOM-1	1020	-	17.8
ECOM-1	317	-	7.7*
ECOM-2	362	16.8	-
ECOM-2	338	20.0	-
ECOM-3	340	13.5	-
ECOM-3	394	13.0	-
ECOM-3	1140	-	17.3
ECOM-3	520	-	7.2*
ECOM-3	336	-	7.0*
ECOM-1A	506	-	8.0*

*IMPROVED SILICONE RESIN CLADDING

TABLE 4.4

ATTENUATION - FINAL MODELS

CABLE TYPE	LENGTH	FIBER#	ATTENUATION OF FIBERS BEFORE CABLING (dB/Km, .79u)*	ATTENUATION AFTER CABLING (dB/Km, .79u)
ECOM-3	536 meters	1	7.6	6.0
		2	6.7	6.8
		3	6.7	6.3
		4	6.8	7.1
		5	6.6	6.3
		6	6.8	8.3
		7	6.7	8.3
		Average	6.8	7.0
ECOM-1	317 meters	1	8.2	8.5
		2	7.1	7.8
		3	6.1	7.4
		4	6.1	7.7
		5	5.9	7.5
		6	5.4	7.5
		Average	6.5	7.7
ECOM-1A	506 meters	1	10.3	8.8
		2	8.2	7.3
		3	7.6	7.9
		4	6.5	7.7
		5	8.2	8.7
		6	7.1	7.6
		Average	8.0	8.0
ECOM-3	1140 meters	1	17.0	14.8
		2	13.8	15.8
		3	19.9	24.4
		4	19.2	17.0
		5	17.4	16.5
		6	19.9	17.8
		7	15.4	15.0
		Average	17.8	17.3
ECOM-1	1020 meters	1	13.1	19.3
		2	13.6	18.2
		3	17.5	18.0
		4	13.5	18.1
		5	14.9	15.8
		6	13.1	17.2
		Average	14.3	17.8
ECOM-3	520 meters	1	5.6	6.0
		2	5.7	6.6
		3	6.2	6.5
		4	7.0	6.6
		5	8.1	7.9
		6	6.3	6.5
		7	11.2	10.6
		Average	7.2	7.2

*FIBERS WOUND ON 4" DIAMETER SPOOLS

in light of prior experience, it was decided to begin testing on preliminary and final models at a level of 1 ft-lb. Table 4.5 summarizes the results of testing.

Results show improvement over earlier cables in that survivability (no breakage) increased from a level of approximately 1.0 ft-lb to that of 1.5 ft-lbs. The external strength member design (ECOM-3) was clearly inferior to the central strength member design, surviving to a level of approximately 1.0 ft-lb. At the MIL-STD loading of 5.0 ft-lbs, approximately 50% of the fibers in the central strength member cables (ECOM-1, 2, and 1A) survived 200 impacts but all of the fibers in the external strength member design (ECOM-3) were broken at approximately 50 impacts.

4.5 Tensile Test

Optical fiber cables must be able to withstand the handling expected in tactical field applications. Manual deployment of the cable, whether from vehicles to ground or strung from poles, require that the cable have high tensile capability. All four cable designs were tested to 400 lbs. in accordance with paragraph 2.1 of the Cable Test Plan. Table 4.6 summarizes the results of testing and clearly indicates that all cable designs are capable of meeting the specified load. In all the samples tested only one break occurred in the gage length, and that occurred in one of the ECOM-1 cables at 350 lbs. In other cables, breaks occurred in the sheaves during clamping since clamp forces required to eliminate slippage were very high. Future revisions in clamping sheaves would be required to eliminate breaks at that

TABLE 4.5

IMPACT TEST

200 IMPACTS

	% FIBERS TRANSMITTING		
	<u>1.0 ft-lbs</u>	<u>1.5 ft-lbs</u>	<u>2.0 ft-lbs</u>
ECOM-1 (15 samples)	100%	100%	90%
ECOM-2 (9 samples)	100%	100%	90%
ECOM-3 (9 samples)	90%	-	10%
ECOM-1A (15 samples)	100%	97%	83%

TABLE 4.6

TENSILE TEST

<u>CABLE TYPE</u>	<u>SAMPLE</u>	<u>NO. BROKEN FIBERS @ 400 lbs.</u>	<u>ACTUAL LOAD AT BREAK</u>	<u>LOCATION OF BREAK</u>
ECOM-1	1	1	350 lbs	in gauge length
	2	0	-	
	3	0	-	
ECOM-2	1	0	-	
	2	0	-	
	3	0	-	
ECOM-3	1	2	-	Broken in Sheaves
	2	1	-	Broken in Sheaves
	3	2	-	Broken in Sheaves
ECOM-1A	1	0	-	
	2	1	-	Broken in Sheaves
	3	0	-	

location.

4.6 Bend Test

Three samples of each of the four cable models were bend tested in accordance with MIL-C-13777F and paragraph 2.4 of the cable test plan. Optical monitoring was recorded on a strip chart recorder and test data is summarized in Table 4.7. Designs 1, 3, and 1A successfully passed the 2000 cycle test while the ECOM-2 design did not. It is believed that breakage in the ECOM-2 design was due to a "pinching" or "crimping" action at the extremes of the bend cycle induced as a direct result of the multilayered structure.

4.7 Twist Test

Three samples of each of the four cable designs were subjected to the twist test in accordance with MIL-C-13777F and paragraph 2.3 of the Cable Test Plan. All twelve of the cables survived more than 2000 cycles without fiber breakage as shown in Table 4.8. One sample of ECOM-1 and ECOM-3 were tested to more than 4000 cycles without failure. One sample of ECOM-2 cable was tested to 5738 cycles with one break occurring at 5300 cycles.

4.8 Temperature Cycling

One sample each of preliminary models, type 1, 2 and 3 were subjected to temperature cycling per MIL-STD-202D (Method 102A, Test Condition D) and paragraph 3.2 of Cable Test Plan C001. As specified in the test plan the samples (between 40 and 52 meters in length) were measured for attenuation at 7900 Angstroms (injection NA of .124) before and after the temperature cycling.

TABLE 4.7

BEND TEST

<u>CABLE TYPE</u>	<u>SAMPLE #</u>	<u>NO. OF CYCLES TESTED</u>	<u>NO. OF BROKEN FIBERS</u>
ECOM-1	1	2030	0
	2	2020	0
	3	2170	0
ECOM-2	1	2030	1 (90 cycles)
	2	2010	1 (620 cycles)
	3	2005	1 (65 cycles)
ECOM-3	1	2047	0
	2	2000	0
	3	2045	0
ECOM-1A	1	2000	0
	2	2000	0
	3	2000	0

TABLE 4.8

TWIST TEST

<u>CABLE TYPE</u>	<u>SAMPLE NO.</u>	<u>NO. OF CYCLES</u>	<u>NO. OF BREAKS</u>
ECOM-1	1	2201	0
	2	2198	0
	3	4017	0
ECOM-2	1	2005	0
	2	2068	0
	3	5738	1 (5300 cycles)
ECOM-3	1	2123	0
	2	2165	0
	3	4182	0
ECOM-1A	1	2000	0
	2	2000	0
	3	2000	0

The following table summarizes the results (a complete summary with individual fiber results is shown in Table 4.9).

<u>Cable Type/Number</u>	<u>Average Attenuation (dB/Km) at 7900Å</u>	
	<u>Before</u>	<u>After</u>
ECOM-1 122975-C	9.8	11.2
ECOM-2 110775-A-Bb	10.9	11.4
ECOM-3 121975-A-IIB	10.5	12.0

Uncertainty in individual fiber measurements is assumed to be about ± 0.1 dB/Km or on the order of ± 2.5 dB for the sample lengths involved.

Although there was a general tendency for individual fiber losses to be slightly larger after the temperature cycling, 5 out of the 19 fibers involved indicated losses slightly less afterwards.

One sample of type 1A was subjected to temperature cycling. The sample (51 meters) was measured for attenuation prior to cycling at .65, .79, and .82, and 1.05 microns. Measurements were made after cycling at the same wavelengths. Data is shown in Table 4.10. The test data indicates a significant increase in attenuation in three of the six fibers in the cable. Testing performed early in the program on preliminary models (ECOM 1 and ECOM 2) of the central strength member design resulted in negligible increases in attenuation after cycling. In the final model ECOM-1A design,

TABLE 4.9
TEMPERATURE CYCLING

<u>Cable Type</u>	<u>Fiber No.</u>	<u>Attenuation @ .79u</u>	
		<u>Before Cycling</u>	<u>After Cycling</u>
ECOM-1 (40 m)	1	8.5	12.6
	2	12.1	11.2
	3	8.7	5.7
	4	10.4	11.1
	5	9.5	14.1
	6	<u>9.8</u>	<u>12.7</u>
	Average	9.8	11.2
ECOM-2 (43 m)	1	9.8	8.3
	2	8.3	9.7
	3	11.5	10.5
	4	17.0	17.7
	5	9.8	9.6
	6	<u>8.8</u>	<u>12.6</u>
	Average	10.9	11.4
ECOM-3 (51 m)	1	12.7	14.4
	2	12.5	13.7
	3	13.4	17.4
	4	15.1	11.4
	5	8.5	7.3
	6	3.5	9.3
	7	<u>7.9</u>	<u>10.5</u>
	Average	10.5	12.0

TABLE 4.10
TEMPERATURE CYCLING
ECOM-1A

FIBER NO.	WAVELENGTH (microns)		
	.65	.79	.82
1	*8.6/79.5	7.5/72.6	11.6/73.8
2	8.7/6.9	7.8/5.7	12.3/11.1
3	9.5/59.0	8.7/57.4	11.2/60.3
4	7.7/26.2	5.5/28.7	9.7/26.4
5	11.5/19.6	11.0/19.8	14.5/24.7
6	8.3/12.9	5.5/10.0	10/6/13.8
			1.05
			20.7/68.6
			22.6/20.8
			19.4/58.8
			16.2/28.7
			22.8/41.0
			16.1/14.8

*ATTENUATION BEFORE CYCLING/ATTENUATION AFTER CYCLING

two distinct differences in cable construction exist:

1. Higher quality, lower loss silicone RTV resin.
2. Use of corrugated MYLAR^R tape instead of TEFLON^R.

The significant increase in attenuation in the ECOM-1A design could be a result of either of the above two variations in design. The possible degradation of the silicone resin is least suspect as fibers have survived immersion for several hours in boiling water. The MYLAR^R tape is a more likely cause since its configuration is that of a corrugated cross section that may have created additional losses in the fiber during the softening of the fiber coatings. The corrugated shape of the tape could very well have caused the softened fiber coating to conform to the corrugations. In order to form positive conclusions, additional testing would be required to verify that the increases in loss were in fact a mechanical effect and not a silicone RTV heat aging effect.

4.9 Moisture Resistance

Moisture resistance testing was performed on preliminary cable models ECOM-1, 2, and 3 in accordance with MIL-STD-202D, Method 106 and paragraph 3.3 of the Cable Test Plan. Samples were prepared by sealing the ends with RTV silicone to prevent moisture entry at that point and metal cable clamps were used to secure the cables during the vibration sub-cycle. During the test some of the cable end seals failed and allowed water to enter. In other samples, the cable clamps were improperly installed and cut the cables during the vibration sub-cycle, again allowing water to enter. Attenuation was measured after testing. However, data was inconclusive. For that reason, moisture resistance testing was

performed on all three final cable models. Additional care was taken to insure that the cable ends were properly sealed to prevent entry of moisture and cable clamps were revised to prevent chafing.

Detailed "before" and "after" data may be seen in Tables 4.11 through 4.13. The average increases in attenuation at $.79\mu$ of 4 to 5 dB/km indicate that moisture does have some affect on attenuation.

<u>Cable Type</u>	<u>Attenuation Before Testing (dB/km, $.79\mu$)</u>	<u>Attenuation after Testing (dB/km, $.79\mu$)</u>
ECOM-1	7.3	12.2
ECOM-1A	7.4	11.3
ECOM-3	6.0	10.3

Additional moisture testing should be performed on cables of longer lengths to minimize the effect of short length testing on attenuation measurements. Additional design and fabrication effort to provide improved vapor barriers should result in cables with less sensitivity to moisture.

4.10 Fungus Testing

All three cable types were fungus tested in accordance with MIL-STD-810B, Method 508, Procedure 1. As specified in the Statement of Work, the cable samples were not cleaned with solvents prior to testing. They were, however, handled with extreme care in that no human contact with the cable surface was made.

The control sample used was untreated goatskin and profuse growth was evident over 100% of the sample. Two of the cable samples

TABLE 4.11
MOISTURE & VIBRATION
ECOM-1
(50 meters)

Fiber No.	WAVELENGTH (microns)		
	.65	.79	.82
1	*10.1/18.9	8.3/15.1	12.6/18.6
2	10.8/17.9	9.8/15.3	14.0/19.0
3	7.1/12.8	5.8/11.4	9.3/13.9
4	9.0/10.9	9.6/7.2	12.4/12.2
5	8.6/**	6.3/**	10.6/**
6	6.6/13.0	3.9/11.0	10.1/13.5
			1.05
			19.0/25.3
			23.3/24.4
			19.9/19.0
			19.7/17.0
			17.5/**
			13.4/17.2

*ATTENUATION (dB/km) BEFORE TESTING/ATTENUATION (dB/km) AFTER TESTING

**UNRELIABLE DATA

TABLE 4.12
MOISTURE AND VIBRATION
ECOM-1A
(56 METERS)

FIBER NO.	WAVELENGTH (microns)		
	.65	.79	.82
1	*8.7/16.1	7.3/12.4	12.0/16.9
2	9.1/12/9	8.0/9.8	12.0/14.7
3	7.7/17.6	6.5/13.8	10.3/16.3
4	8.5/13.6	6.2/11.2	10.6/16.1
5	10.2/11.4	9.2/10/0	13.9/12.7
6	7.8/13.3	7.2/10/4	11.7/13.9
			1.05
			16.9/24.5
			21.6/22.1
			18.7/16.9
			17.3/23.1
			24.7/21.8
			23.9/20.9

*ATTENUATION (dB/km) BEFORE TESTING/ATTENUATION (dB/km) AFTER TESTING

TABLE 4.13
MOISTURE & VIBRATION
ECOM-3
(41 meters)

FIBER NO.	WAVELENGTH (microns)		
	.65	.79	.82
1	*5.36/9.4	1.84/7.1	6.1/10.5
2	10.6/11.5	9.1/7.8	12.2/10.6
3	**1.6/13.2	**/10.3	**2.9/14.2
4	8.8/13.5	5.5/8.7	10.0/13.0
5	6.8/16.6	6.8/13.6	9.7/16.7
6	5.9/16.2	4.3/13.6	7.2/17.2
7	5.6/13.2	4.1/10.8	7.1/11.2
			1.05
			6.6/16.1
			13.5/7.0
			** 1.0/19.1
			14.9/10.2
			15.3/19.7
			5.0/22.2
			4.5/22.3

*ATTENUATION (dB/km) BEFORE TESTING/ATTENUATION (dB/km) AFTER TESTING

**UNRELIABLE DATA

showed no growth (ECOM-3 and ECOM-1A) while the third (ECOM-1) showed growth over at least 90% of its surface area. The growth appeared as a discoloration of the surface rather than a profuse "fuzzy" growth. The batch number of the polyurethane material used for the jacket was given to the vendor; his records do not indicate that any process changes took place that may degrade fungus resistance. The supply of that particular batch number was depleted during final model fabrication.

Based on the above, it may be assumed that:

1. The batch of polyurethane was contaminated, or:
2. The cable sample came in contact with a contaminant during the fabrication.

Several possible sources exist:

- a. Extruder tooling
- b. Water trough
- c. Capstan
- d. Takeup reels

The vendor subsequently performed a fungus test at his facility using a recently fabricated polyurethane jacketed cable. The test resulted in no growth on the cable samples.

4.11 Nuclear Survivability Testing

In actual combat situations, fiber optic cables may be subjected to radiation exposure. Cables produced under the low cost cable contract were evaluated jointly by ITT and Naval Research Laboratory personnel using NRL equipment in order to determine the ability of plastic clad silica fibers to provide continuous

operation under adverse conditions.

4.11.1 Test Plan

To simulate tactical field conditions, it was agreed upon to use the NRL Linac as a source of mixed flux neutrons and gamma radiation for the nuclear survivability testing of plastic clad silica fibers. The Linac is used to simulate the fission spectrum from a weapon by irradiating a water cooled target with a 22 Mev electron beam. The Linac's neutron output has a distribution of energies and to obtain the 1 Mev silicon damage equivalent from the total fluence, a correction factor of less than 10% is needed. The original intent was to irradiate two samples and the radiation induced optical losses to be measured 10 seconds and 24 hours after irradiation. One sample was to be irradiated to 10^3 rads while the other was to be exposed to 10^5 rad level within a period of 10 seconds. During the course of testing, it was found necessary to irradiate several fibers with intermediate doses of either mixed flux or high energy electrons to obtain additional information about radiation hardening and saturation of induced optical losses in the fibers under investigation. Because long gauges of cables are needed to conduct the test, and the volume in the radiation facility where uniform flux can be achieved is limited, it was necessary to perform the nuclear survivability test on fibers only. However, a short section of each cable design was irradiated to a mixed flux irradiation to study any adverse effect in the cable mechanical integrity and its components.

4.11.2 Experimental Setup

4.11.2.1 Radiation Source

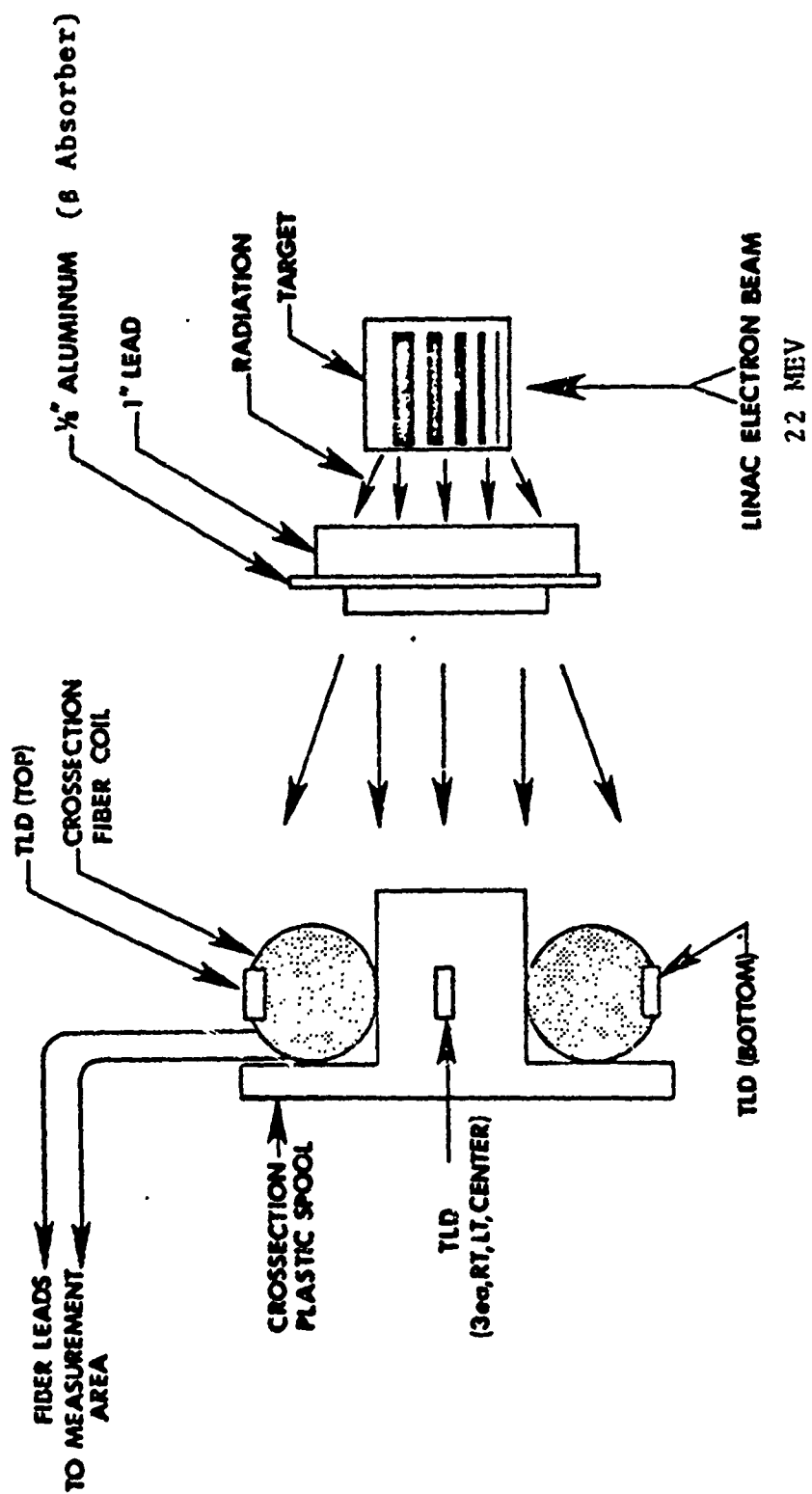
NRL linear accelerator (Linac) was used as a radiation source by making use of the electron-produced Bremsstrahlung (x-rays). The Linac has high power neutron irradiation capability which simulates a fission-neutron spectrum and the associated gamma rays.

Bombardment of a heavy-element target with high energy electrons from a Linac produces, through Bremsstrahlung and subsequent photo-neutron emission, neutrons having an energy distribution quite similar to a fission spectrum.

The target for the neutron and gamma irradiation facility at NRL electron Linac was selected to be approximately 8 radiation lengths thick (53 gm/cm^2). It consists of tantalum plates whose thicknesses are graded to distribute more uniformly the energy deposited in them by the traversing electrons. The plates are equally spaced in a water cooled aluminum box as shown in Figure 4-1.

The electron beam (22 Mev) was impinged on the target at a rate of 360 bursts per second with an average current of about 50 micro-amps. The target was electrically isolated from its surrounding and for a given run the accumulated charge on the target was measured with a Keithley electrometer.

Both charge integration and sulfur disk activation were used to monitor the beam fluence.



LOCATION OF FIBER OPTIC COIL WITH
RESPECT TO THE TARGET

FIGURE 4-1

4.11.2.2. Mixed Flux Neutrons and Gamma Radiation

The electron beam was directed onto the tantalum target. The coiled fiber axis was placed perpendicular to the beam axis, about 2 1/2" from the target. In the low level irradiation experiment ($\leq 10^3$ rads), 1" lead brick was placed between the coiled fiber and the target. The location of the fiber coil with respect to the target is shown in Figure 4-1. The linac pulse rate was 360 pps. All irradiations were performed in less than 10 seconds except when irradiation levels higher than 10^5 rads were to be achieved.

4.11.2.3 Pure Gamma Irradiation

To simulate the effect of gamma radiation on the induced optical loss of the fiber, high energy electrons from the Linac were used at 40 Mev. An aluminum scatterer was placed in the electron beam to produce homogeneous flux around the coiled fiber. The fiber coil axis was placed on the electron beam axis approximately one meter from the scatterer.

4.11.2.4 Dosimetry

The gamma dose received by the coiled fiber was measured by placing four thermo-luminescent dosimeters (TLDs) equally spaced on the coil and a fifth dosimeter at the coil's center. The locations of the TLDs on the coil are shown in Figure 4-1. The dose was calculated by averaging the five values. The TLDs were calibrated for rads of Si damage equivalent using the

NRL Co⁶⁰ source. All gamma doses in this report are expressed in units of absorbed dose, rads of Si damage equivalent.

The neutron fluence was determined by the activation of sulfur discs. Four discs were equally spaced on the coiled fiber. The discs were supplied and analyzed by EG & G. The average values of the four measurements were reported.

4.11.2.5 Fiber Preparation

Two types of fibers were tested. Each employed Suprasil^R core but differed in the type of silicone RTV applied. The first silicone RTV shall be referred to as Silicone A (Dow-Corning Sylgard^R) and the second (a higher optical quality material) shall be referred to as Silicone B (Shin-Etsu). Both fibers were jacketed with a secondary coating of PFA. The fibers were coiled to the specified length on 2" barrel spools with one flange cut off to expose the fiber to radiation. The reported fiber length is only that of the coiled section of fiber. The two ends of the fiber were run through a conduit from the irradiation area to the shielded measuring area. To monitor the induced optical losses at different radiation levels, coils of different lengths of the same fiber type were prepared. The optical losses before and 24 hours after irradiation were measured at ITT-EOPD at .79 microns and

.82 microns. The injection NA was .124.

The dynamic optical loss measurements after irradiation were done on the Linac site using a white light, monochromator and PIN photo-detector. The optical losses were monitored at .82 microns with injection NA=.18. The signal from the detector was fed to a strip chart recorder to monitor the optical power from the fiber as a function of time.

4.11.2.6 Dynamic Optical Loss Measurements

End preparation was performed on the two leads from the coiled fiber. This was accomplished by stripping the PFA and the silicone RTV jackets and the break was induced by scribing the fiber under tension with a diamond tip. The ends were examined under an optical microscope to insure that the break produced a flat, mirror finish. One end was secured in the detector, and the other end was injected with .82 micron light from a monochromator and a microscope objective. The injection NA was .18. The position of the input end of the fiber was adjusted to achieve maximum injection power. The power level as a function of time was monitored using a strip chart recorder. When a coiled fiber is exposed to the radiation from the Linac, a spontaneous drop in the optical power takes place with immediate recovery after shutting down the Linac. The induced optical loss as a function of time is calculated from optical

power after irradiation P_t , optical power before irradiation P_o , and the length of the fiber, L , in kilometers.

$$\text{Induced optical loss} = \frac{10}{L} \log \frac{P_o}{P_t} \text{ dB/km}$$

As the radiation induced optical losses were higher than anticipated, it was necessary in some tests to switch to the appropriate scale on the chart recorder and adjust for the zero point, which required about 30 sec. In such case the 10 second point was not recorded, but an approximate value can be determined by extrapolation.

4.11.3 Results

The scope of this experiment was to test and analyze the radiation induced optical losses in plastic clad silica fibers employing two types of silicone cladding materials. These fibers were irradiated to gamma and neutron mixed flux irradiation levels of 10^2 to 10^5 rads of gamma and 10^8 to 10^{10} neutrons/cm² ($E > 10$ Kev). The radiation induced optical loss at .82 microns was monitored as a function of time with special emphasis on the optical losses 10 seconds and 24 hours after irradiation.

To study the effect of gamma radiation on the fiber optical losses, the fibers were irradiated with high energy electrons, to simulate the effect of gamma rays.

The optical power recovery, in the two types of fibers irradiated to either mixed flux neutrons and gamma or high energy electrons, as well as the optical losses 10 seconds and 24 hours after irradiation, will be discussed.

4.11.3.1 Induced Optical Losses - 10 sec. After Irradiation:

4.11.3.1.1 Mixed Flux Irradiation

Table 4.14 shows the mixed flux radiation induced optical loss at .82 microns 10 seconds and 24 hours after irradiation. Tests 1 through 6 were performed on Silicone B coated Suprasil fibers and tests 7 through 12 were conducted on Silicone A coated Suprasil fibers. For each fiber type short, medium, and long fibers were tested to study the radiation effects at different dose levels.

The gamma dose is given in microcoulomb and rads of silicon damage equivalent which was measured using TLDs. The neutron dose was measured using the activation of sulfur discs for neutrons with energies >10 kev. Higher dose rates were achieved by removing the lead brick which shields the fiber coil. The optical losses 10 sec after irradiation were higher than those predicted from previous measurements on short fiber gauges and irradiated to high levels of pulsed irradiation¹. The effect will be discussed in Section 4.11.3.1.2

¹Radiation Resistance of Fiber Optics Materials and Waveguides, B.D. Evans, G.H. Sigel, Jr. "IEEE Transactions on Nuclear Science" Vol. NS-M22, 2462, 1975.

TABLE 4.14
RADIATION INDUCED OPTICAL LOSS IN PLASTIC CLAD SILICA FIBER
NEUTRONS AND GAMMA MIXED FLUX PULSED IRRADIATION

TEST NUMBER	1	2	3	4	5	6	7	8	9	10	11	12
Fiber Type												
Intrinsic Loss	5.5 dB/km											
Induced Optical Loss 10 Seconds After Irradiation (dB/km)	-	-	-	86	-	21.2	-	65	-	13.7	5.8	-
Induced Optical Loss 24 Hours After Irradiation (dB/km)	-25	-	-	-0.49	-	0.7	-44	-	-1.11	-	+1.5	+3.67
Absorbed Gamma Dose Using TLB in μC in rads	10.44 0.89×10^3	12.08 1.0×10^3	18.34 1.56×10^3	104.3 8.9×10^3	1519.7 1.3×10^5	1695.3 1.4×10^5	6.010 $.51 \times 10^3$	12.962 1.1×10^3	104.8 8.9×10^3	0.867 74	8.31 $.76 \times 10^3$	1854.6 1.6×10^5
Neutron Dose with Energies >10 KeV (ntn/cm^2)	3.4×10^8	6.8×10^9	$<11 \times 10^8$	E 5.5×10^9	E 4×10^{10}	E 5×10^{10}	1.7×10^9	E 6.8×10^9	E 5.5×10^9	$<11 \times 10^8$	4.2×10^9	E 1.3×10^{10}
Exposure Time in Seconds	5.5	5.5	0.5	2.5	18.1	24.8	5.5	5.5	2.5	.5	5.5	6
Shield Thickness	1" Pb	1" Pb	No Pb	No Pb	No Pb	No Pb	1" Pb	1" Pb	No Pb	1" Pb	1" Pb	No Pb
Fiber Length (in meters)	854	300			40		877	274		299		40

E = Estimated Neutron Dose

Figure 4-2 shows the optical power recovery in 854 meters of Silicone B coated fiber after a mixed flux radiation dose of 8.9×10^2 rads of gamma and 3.4×10^8 n/cm² neutrons. The power was monitored about 80 seconds after irradiation, and shows approximately 43 dB/km induced optical loss. Extrapolating the recovery curve to 10 seconds after irradiation would indicate about 80 dB/km induced optical loss as compared to 1 dB/km predicted from previous measurements¹. The optical loss decreases to about 1 dB/km after 30 minutes.

Figure 4-3 shows optical power recovery in 299 meters of Silicone A coated fiber after irradiation with a low dose level. Curve 10 shows the recovery after irradiating with 74 rads. The induced optical loss after 10 seconds is about 14 dB/km. After recovery and irradiating with 760 rads (Test 11) the 10 second point increased to about 58 dB/km. The radiation hardening is negligible in Test 11, because the fiber preirradiation dose was too low.

The effect of medium dose levels, 10^3 to 10^4 rads, on the optical power recovery in 300 meters of Silicone B coated fiber are shown in Figure 4-4. The fiber was irradiated with 10^3 rads and monitored 3 minutes after irradiation, as shown as Test 2 in Figure 4-4. Extrapolation to 10 seconds after irradiation showed an induced loss higher than 100 dB/km. The fiber was allowed to recover and then irradiated to a dose which was about 50% higher than the Test 2 dose. The recovery curve is

¹Ibid

GAMMA AND NEUTRON MIXED FLUX IRRADIATION

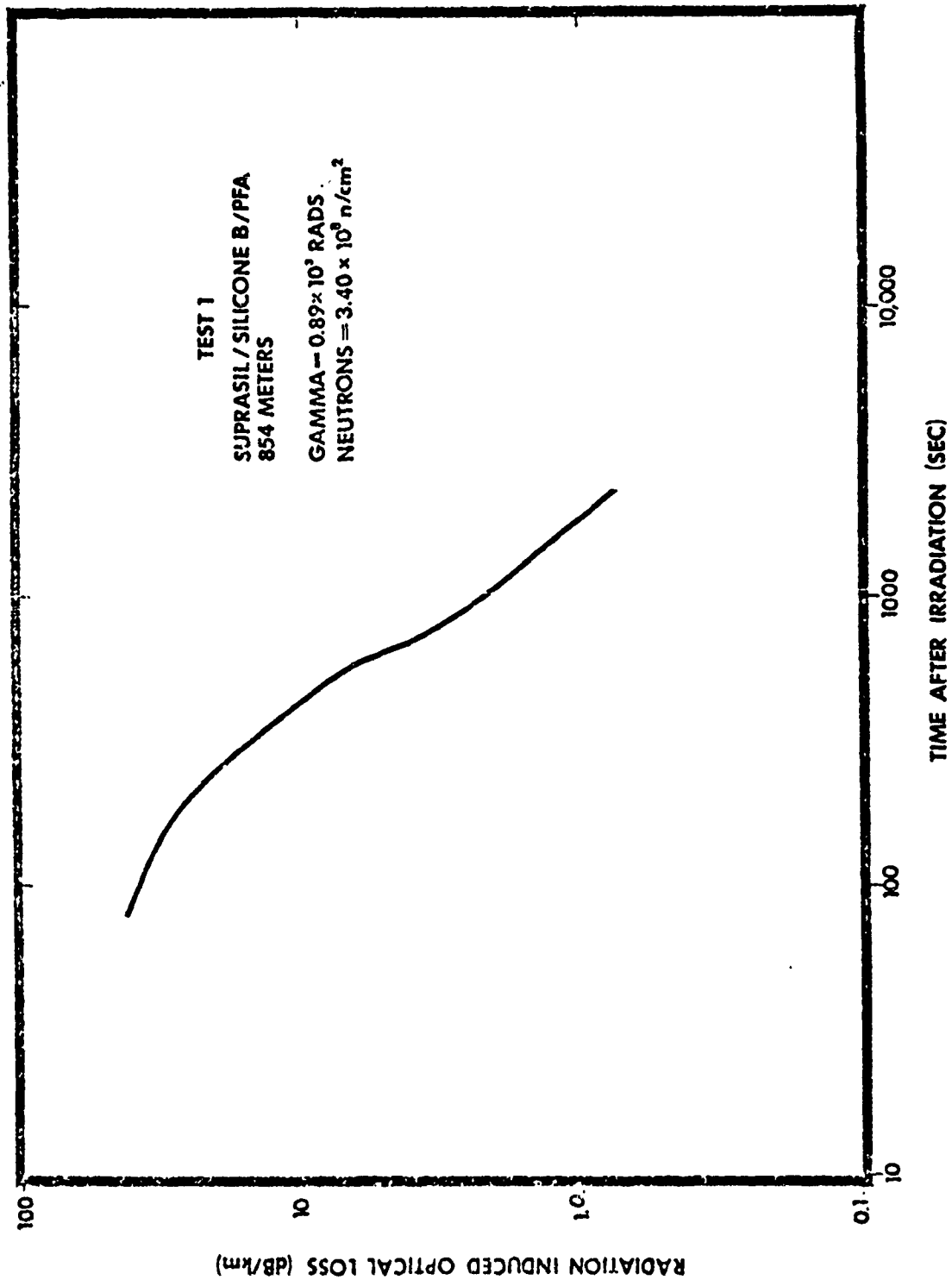


FIGURE 4-2

GAMMA AND NEUTRON MIXED FLUX IRRADIATION

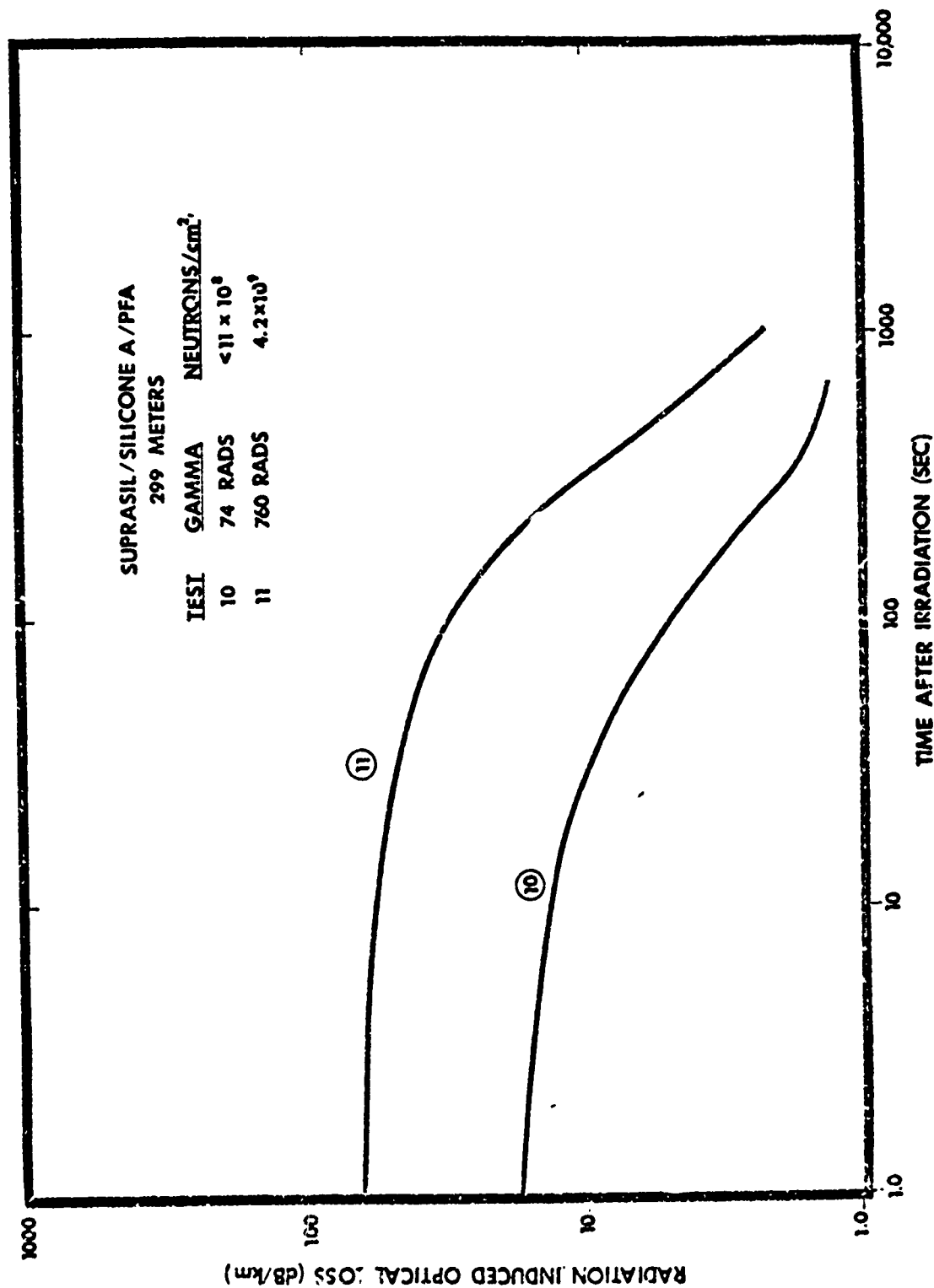


FIGURE 4-3

GAMMA AND NEUTRON MIXED FLUX IRRADIATION

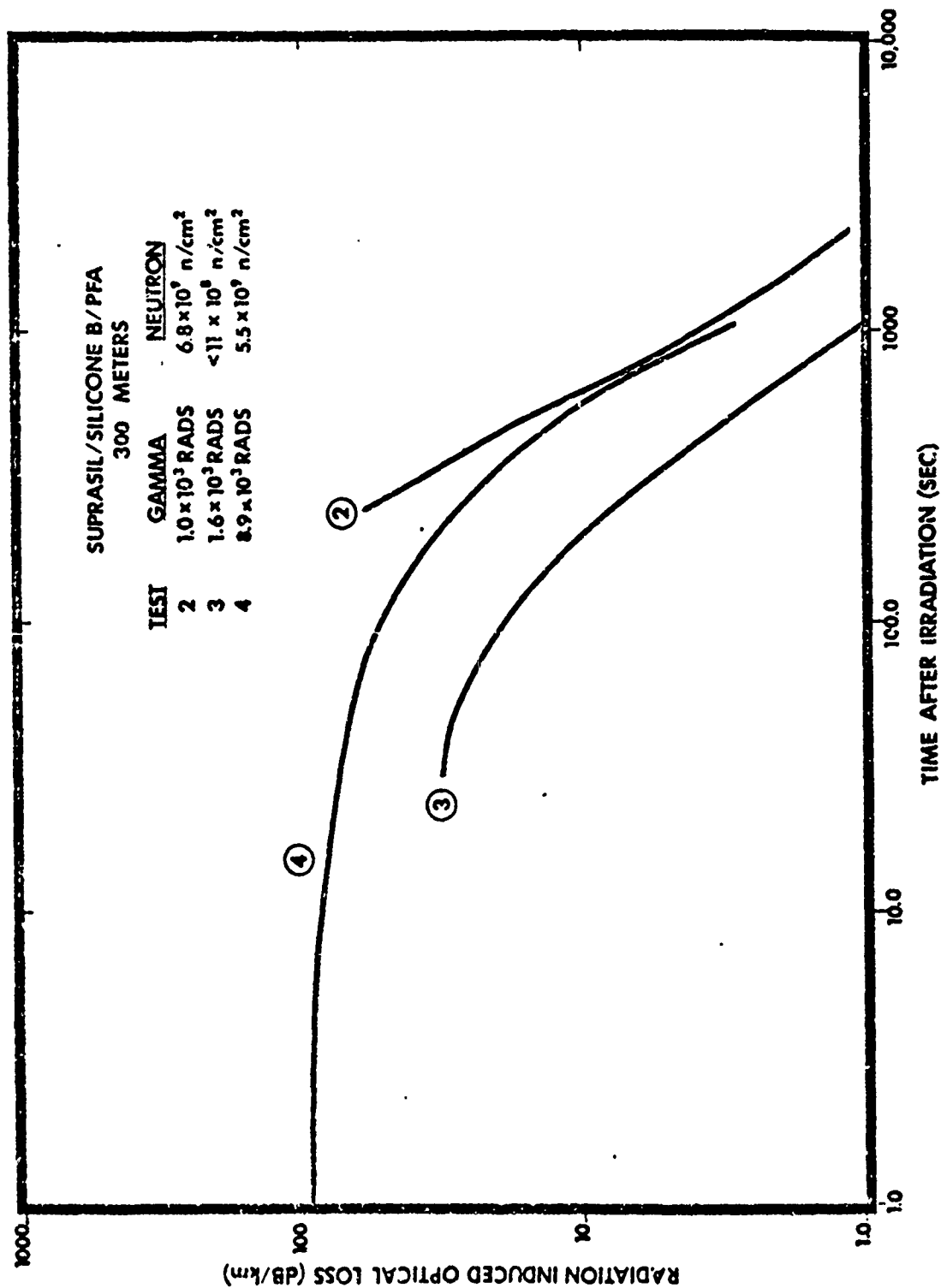


FIGURE 4 - 4

shown in Test 3 Figure 4-4. The extrapolated optical value at 10 seconds is less than 50 dB/km. In Test 4, the fiber was irradiated after recovery to about 10^4 rads. The optical power was monitored immediately after irradiation. The 10 second value is higher than that of Test 3, but is lower than that of Test 2. This is an indication of saturation effect or an increase of the radiation hardness of the fiber by preirradiation.

The effect of high radiation dose levels $\sim 10^5$ in a short gauge length of Silicone B coated fiber is shown in Figure 4-5. It can be seen that optical losses are lower in the second irradiation, Test 6, as compared to the first irradiation, Test 5, even though the second radiation dose is slightly higher than the first dose. The radiation hardening has been demonstrated again and indicates that the radiation hardening increases with radiation dose.

The optical power recovery after irradiating 950 meters of Silicone A coated fiber with 5×10^2 rads is shown in Figure 4-6, Test 7. Test 1 for a Silicone B coated fiber is shown on the same figure for comparison. The extrapolated 10 second point for Test 7 is also higher than predicted from previous tests on high purity silica. The two recovery curves 1 and 7

GAMMA AND NEUTRON MIXED FLUX IRRADIATION

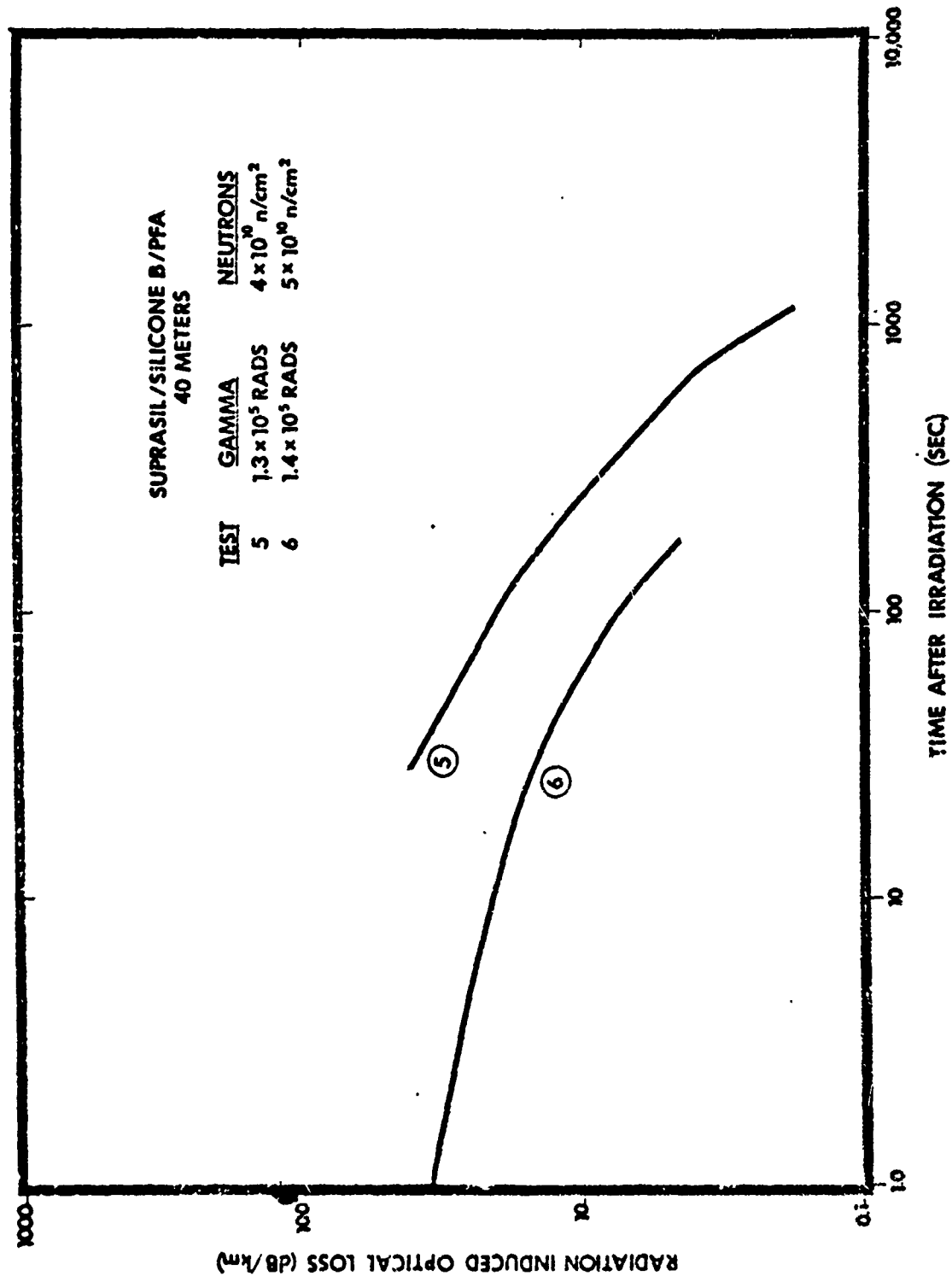


FIGURE 4-5

GAMMA AND NEUTRON MIXED FLUX IRRADIATION

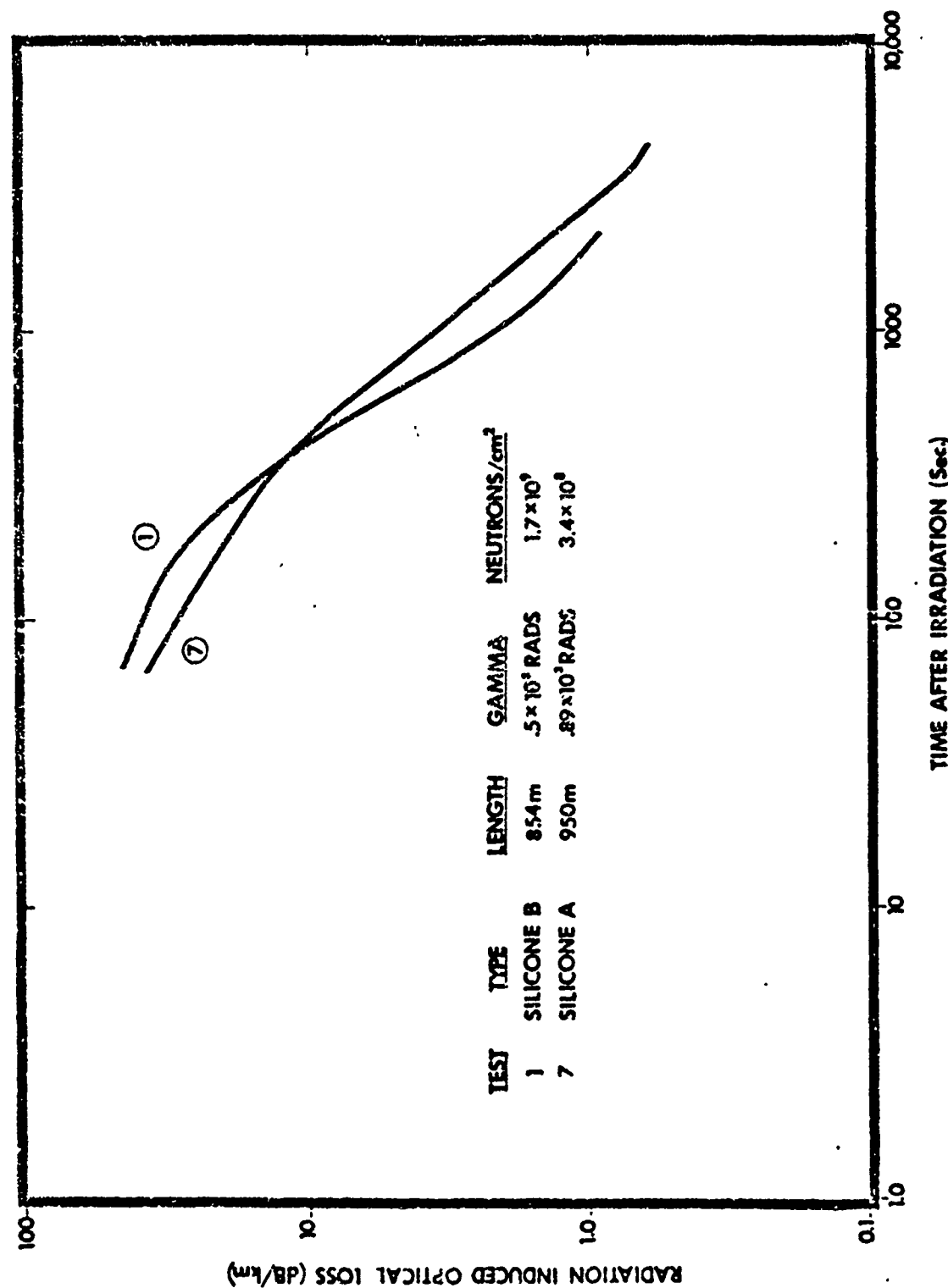


FIGURE 4 - 6

are similar except for the crossing of two curves which indicates a faster recovery in the Silicone B coated fiber.

Figure 4-7 Tests 8 and 9 show the optical power recovery of 274 meters of Silicone A coated fiber after mixed flux irradiation. In Test 8, the fiber was first irradiated with 1.1×10^3 rads of gamma and 6.8×10^9 n/cm². The induced optical loss 10 seconds after irradiation is 65 dB/km. Test 9 shows the induced optical loss after reirradiating the same sample after recovery to 8.9×10^3 rads of gamma and 5.5×10^9 n/cm². The induced optical loss after 10 seconds has increased to more than 150 dB/km which indicates that preirradiating to 10^3 rad levels is not enough to develop significant radiation hardening.

The optical power recovery of a fiber irradiated to a much higher dose is shown in Test 12, Figure 4-7 for comparison. In this test, a 40 meter silicone coated fiber was irradiated for the first time to 1.6×10^5 rads of gamma and 1.3×10^{10} n/cm². It is clear from Figure 4-7 that the fiber irradiated to a higher dose (Test 12) has a lower induced loss than that of the sample irradiated to a lower dose (Test 9). One may conclude that radiation hardening is evident at high radiation doses. The hardening process was first observed on preirradiated fiber and it was thought that the radiation hardening process may take place after preirradiation. Test 12 confirms, however, that the radiation hardening is taking place during first-time high dose irradiation.

Figure 4-8 shows a retrace of Test 8. In this test, the optical power was monitored during and after irradiation. It is

GAMMA AND NEUTRON MIXED FLUX IRRADIATION

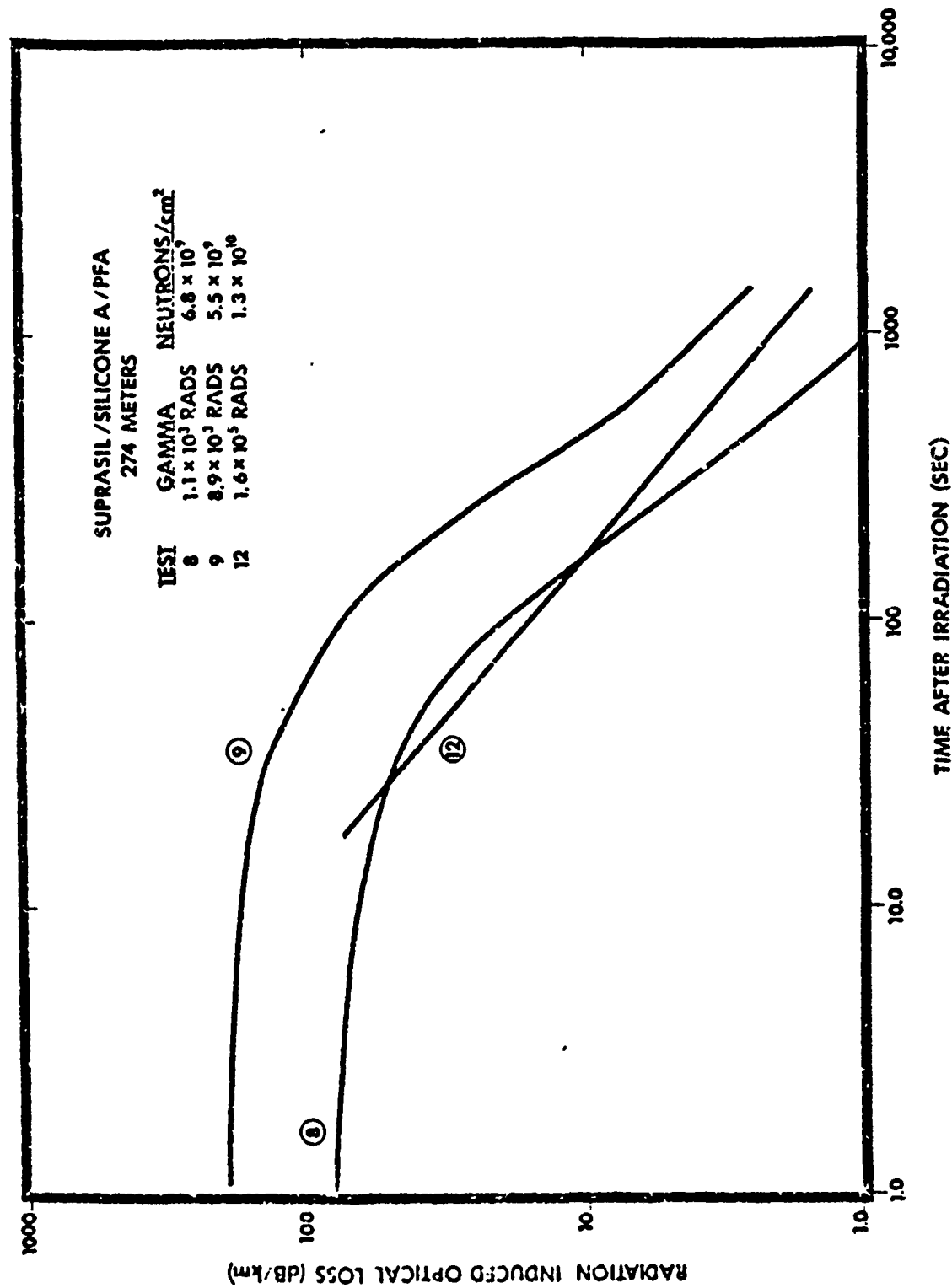


FIGURE 4-7

GAMMA AND NEUTRON MIXED FLUX IRRADIATION

SUPRASIL/SILICONE A / PFA
299 METERS

TEST	GAMMA	NEUTRONS/cm ²
8	1.1×10^3	6.8×10^9

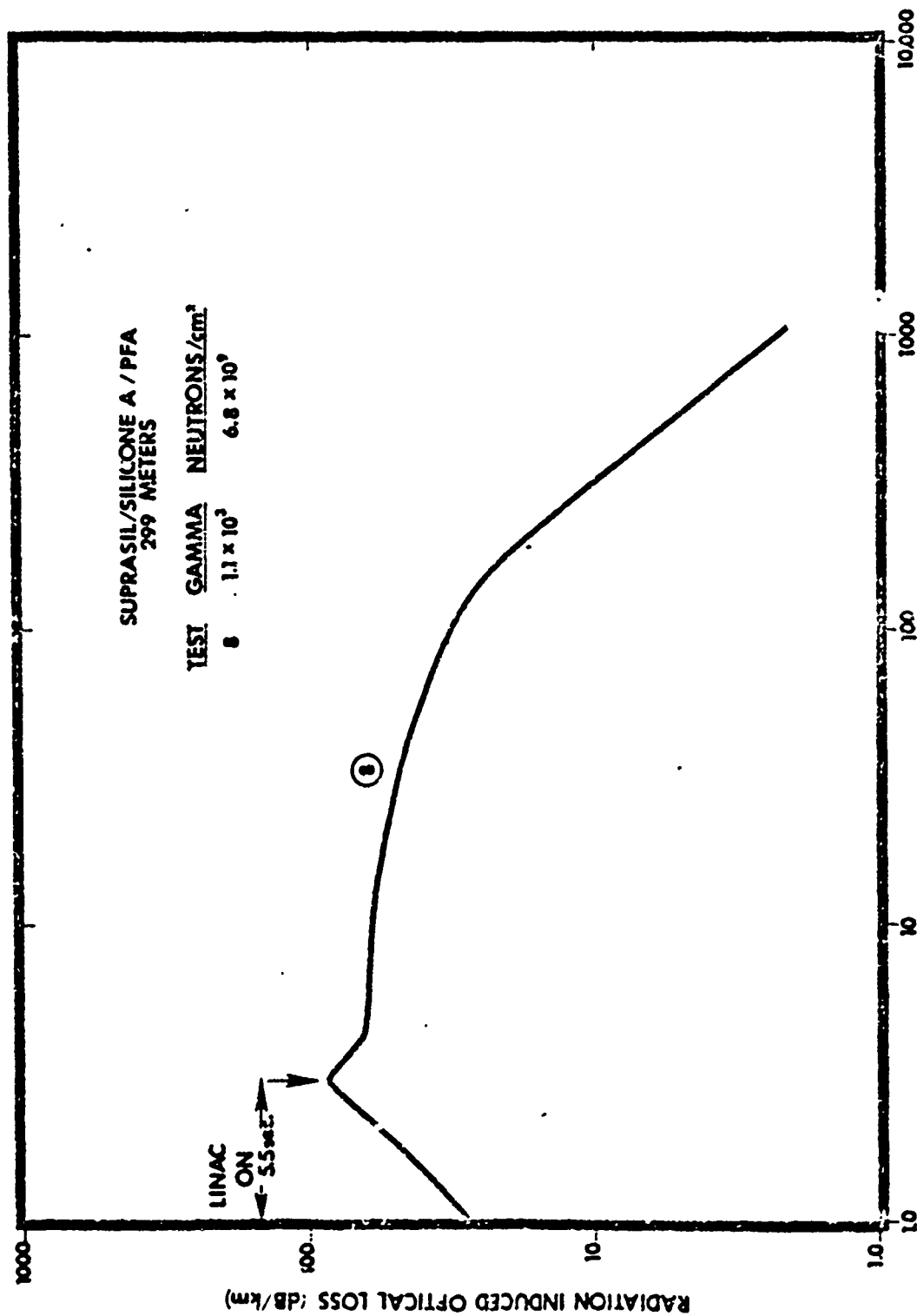


FIGURE 4-8

interesting to notice a fast recovery mechanism in the first two seconds after irradiation followed by a second but slower recovery mechanism afterward. In the initial recovery mechanism, the induced optical loss was lowered by 24 dB/km in about 2.5 seconds.

The radiation induced optical losses 10 seconds after irradiation, measured or determined from extrapolation, are shown in Table 4.15 for the tests described in Table 4.14. The gamma radiation doses are also listed in the table. The induced optical loss, dB/km rad, in the fourth column is calculated by dividing the induced loss in dB/km by the dose in rads. The neutron dose was not considered because 10^9 n/cm² 1Mev neutrons would be equivalent to 1 rad, therefore their effect is not substantial. The induced optical loss values in dB/km-rad from Table 4.15 were plotted as a function of dose for the eleven tests and are shown in Figure 4-9. Interestingly, we notice a decrease in induced loss, dB/km-rad, with increasing dose. This observation indicates a saturation effect in the optical fiber at a dose much below the value reported for bulk silica, which is about 10^6 - 10^7 rad.

4.11.3.1.2 Gamma Irradiations

Gamma radiation reacts with electrons in the glass to produce secondary electrons. The redistribution of electrons in the glass creates positive holes and electron traps (color centers, possibly on defect sites.) The same effect can be simulated

TABLE 4.15

INDUCED LOSS
MIXED FLUX

TEST #	GAMMA DOSE (rads)	INDUCED OPTICAL LOSS (dB/km) AFTER 10 Sec.	INDUCED OPTICAL LOSSES (d B/km-rad)
1	8.9×10^2	75	8.4×10^{-2}
2	1.0×10^3	-	-
3	1.56×10^3	38	2.4×10^{-2}
4	8.9×10^3	87	9.7×10^{-3}
5	1.3×10^5	67	5.1×10^{-4}
6	1.4×10^3	21.5	1.5×10^{-2}
7	5×10^2	80	1.6×10^{-1}
8	1.1×10^3	40	3.6×10^{-2}
9	8.9×10^3	175	1.96×10^{-2}
10	74	13.5	1.8×10^{-1}
11	7.6×10^2	59	7.6×10^{-2}
12	1.6×10^5	13	8.1×10^{-4}

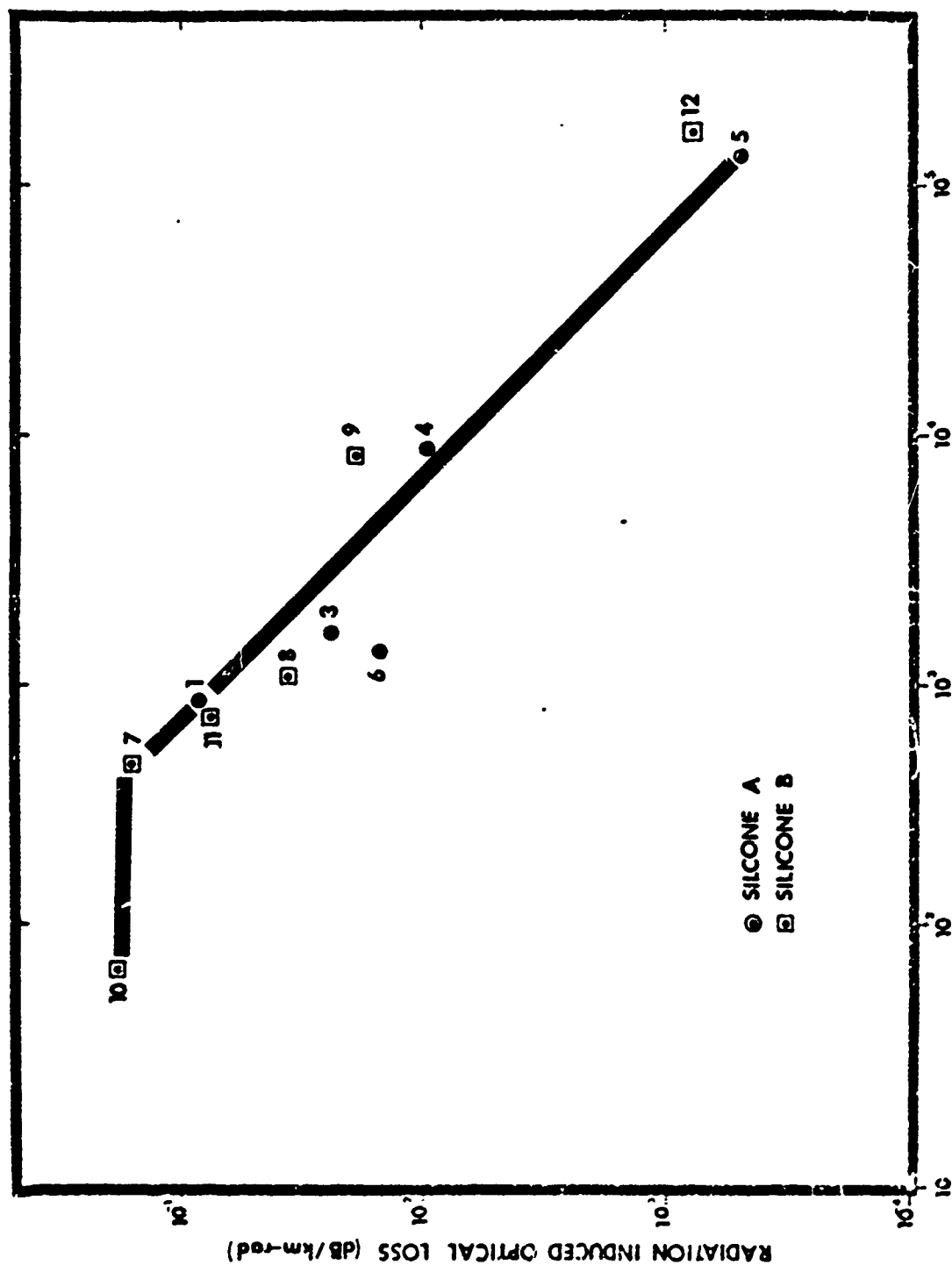


FIGURE 4-9

using high energy electrons and electron-electron interaction instead of gamma-electron interaction. This experiment was designed to study the effect of gamma radiation alone and was intended to provide an indication of the level of contribution of the neutrons to the radiation damage.

Electrons from NRL Linac were used with energies about 40 Mev to simulate the effect of gamma rays.

Table 4.16 shows the effects of high energy pulsed electrons on the optical losses in plastic clad silica fibers. Tests 1 to 3 were performed on 99 meters of Silicone A coated fibers and Tests 4 to 7 were conducted on 94 meters of Silicone B coated fibers. Radiation dose, exposure time, and the induced optical losses 10 seconds and 24 hours after irradiation are also shown in Table 4.16.

Figure 4-10 shows the optical recovery of 99 meters of Silicone A coated fiber irradiated to 3 radiation doses of high energy electrons. The sample was first irradiated to 8.3×10^2 rads, Test 1, and the induced optical loss at 10 seconds was 88.5 dB/km. The second irradiation, Test 2, after Test 1 and recovery was 9×10^4 rads. Because of the cross over of plots 1 and 2, it is expected that the induced optical loss 10 seconds after irradiation for Test 2 to be greater than 88 dB/km.

TABLE 4.16
RADIATION INDUCED OPTICAL LOSS IN PLASTIC CLAD SILICA FIBERS
HIGH ENERGY PULSED ELECTRONS

TEST NUMBER	1	2	3	4	5	6	7
Fiber Type	Suprasil/Silicone A/PFA 17 dB/km		Suprasil/Silicone B/PFA 6.5 dB/km				
Intrinsic Loss							
Induced Optical Loss 10 sec. After Irradiation (dB/km)	88.5	-	30.5	86	34	18.2	94
Induced Optical Loss 24 Hours After (dB/km)			+0.61				+20.6
Absorbed Gamma Dose Using TLD							
in μC	9.782	1060.8	1019.5	15.00	15.88		
in rads	$.83 \times 10^3$	9.0×10^4	8.6×10^4	1.3×10^3	1.35×10^5	1.3×10^3	1.35×10^5
Exposure Time In Millisec.	5.5	555.5	555.5	5.5	555.5	5.5	555.5
Fiber Length	99 meters		94 meters				

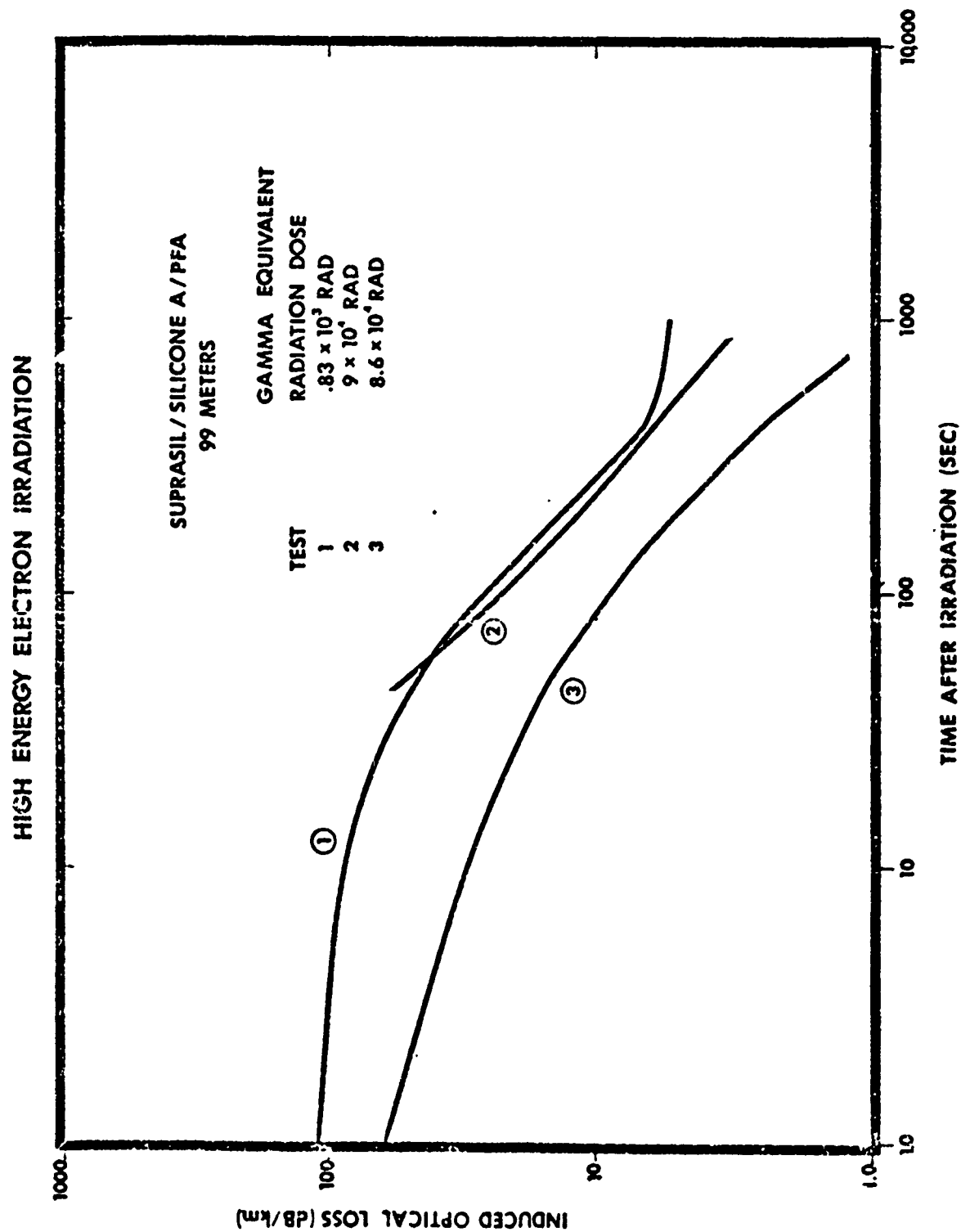


FIGURE 4-10

The third irradiation dose, which is comparable in level to that of Test 2, was applied to the fiber after recovery. The induced optical loss was lower than those of the first two irradiations and was 30 dB/km 10 seconds after irradiation. This indicates an increase of the radiation hardness of the preirradiated samples.

The effects of four different doses on the induced optical losses in a Silicone B coated fiber are shown in Figure 4-11. The sample length was 94 meters and the optical power level was monitored continuously. The sample was first given 1.3×10^3 rads and the induced optical loss after ten seconds was 86 dB/km at .82 microns as shown in Figure 4-11 Test 4. The induced loss after 10 seconds was much lower (34 dB/km) as shown in Test 5 after Test 4 and recovery and a second irradiation to a higher dose of 1.35×10^5 rads. To study the effect of a low radiation dose on a preirradiated sample, the same sample was given 1.3×10^3 rads after recovery. The induced optical loss after 10 seconds was 18 dB/km, as shown in Figure 4-11 Test 6 compared to 86 dB/km when the sample was given the same dose for the first time. The fourth exposure was a high dose of 1.35×10^5 rads and the induced optical loss after 10 seconds is 24 dB/km as indicated in Figure 4-11 Test 7. Again the induced optical loss after the second high radiation

HIGH ENERGY ELECTRON IRRADIATION

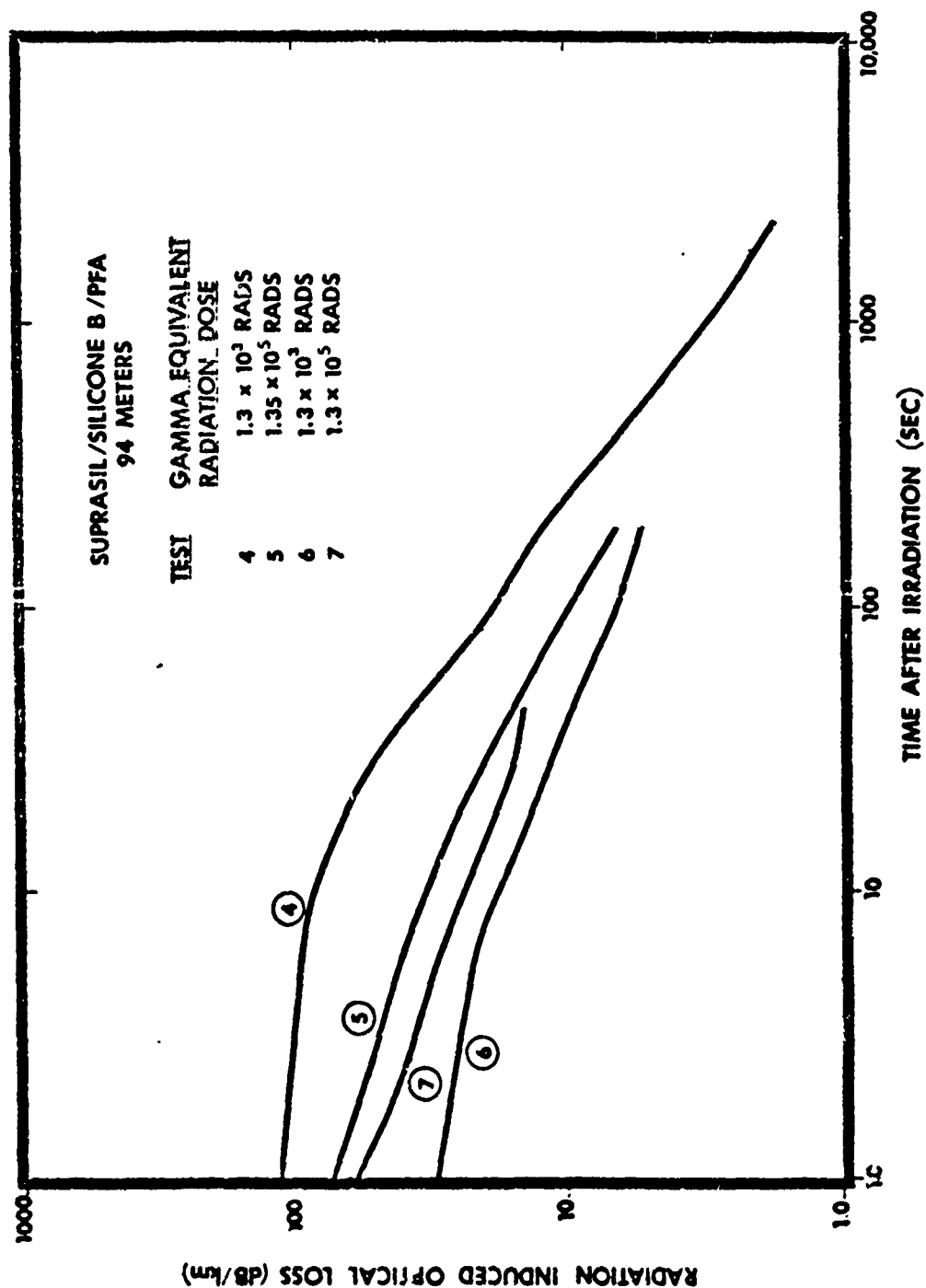


FIGURE 4-11

is lower than that after the first high dose.

It is believed that the testing under this contract was the first performed on long lengths of optical fibers at low levels of radiation dose. In contrast, previous experiments were conducted on short lengths of fibers exposed to high doses. Based on the published results of that testing, and the commonly held belief that induced optical loss in glass is linear at radiation levels below 10^6 rads, it was predicted by extrapolation that induced optical losses at low doses would be lower than that actually measured in testing under this contract.

The above results indicate that the virgin unirradiated fiber is sensitive to low levels of radiation. This is the case in the mixed flux irradiation experiment, and the effect is confirmed with results from high energy electron irradiations. After irradiating the fiber to a high dose of radiation, the fibers showed lower radiation induced optical losses and higher rates of recovery, compared to the first irradiation

Table 4.17 shows the induced optical loss in dB/km-rad and radiation doses in rads for the high energy electrons radiation tests performed on Silicone A and Silicone B coated fibers. Figure 4-12 shows a plot of radiation induced optical loss as a function of radiation dose in rads. The points approximate a straight line when plotted on log-log paper. The decrease

TABLE 4.17

INDUCED LOSS

HIGH ENERGY ELECTRONS

TEST #	GAMMA D (rads)	INDUCED OPTICAL LOSS (dB/km) - 10 SEC. AFTER IRRADIATION	INDUCED OPTICAL LOSS (dB/km-rad)
1	8.3×10^2	87	1×10^{-1}
2	9.0×10^4	-	-
3	8.6×10^4	31	3.6×10^{-4}
4	1.3×10^3	85	6.5×10^{-2}
5	1.35×10^5	34	2.5×10^{-4}
6	1.3×10^3	18	1.38×10^{-2}
7	1.35×10^5	24	1.7×10^{-4}

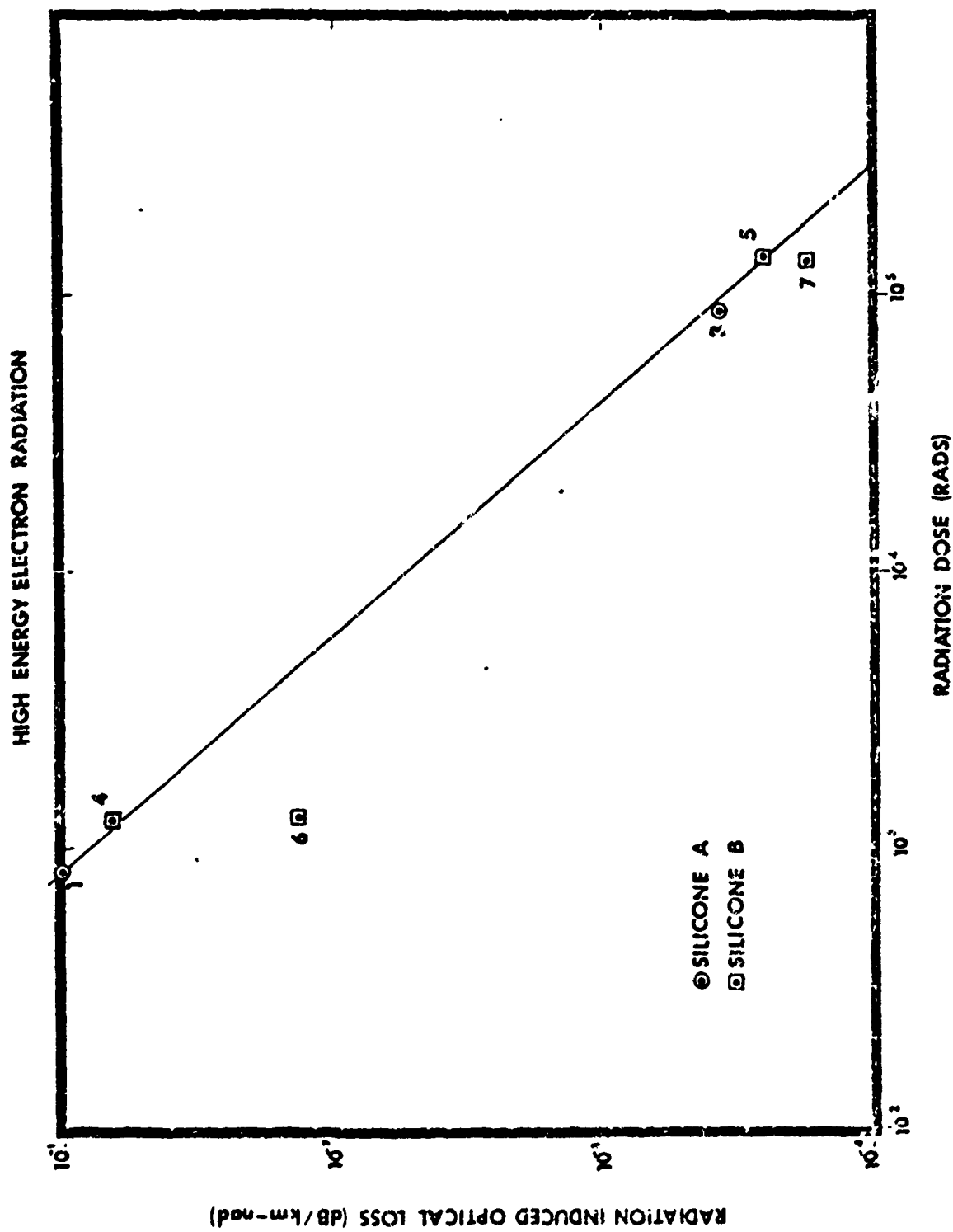


FIGURE 4-12

in induced loss in dB/km-rad with increasing radiation indicates a saturation effect is present within the radiation dose range studies. An induced loss after 10 seconds, of 18 dB/km was measured in the preirradiated sample (Test 6) compared to 85 dB/km for the virgin sample (Test 4). Both samples were irradiated to the same dose of 1.3×10^3 rads. This observation demonstrates the radiation resistance of the preirradiated fibers which is due to radiation hardening.

4.11.3.2 Radiation Induced Optical Losses After 24 Hours

A total of eleven fibers were irradiated to doses ranging from 74 rad to 2.7×10^5 rad. The induced optical losses and accumulated doses are shown in Table 4.18.

The radiation induced losses in these fibers are within experimental error and the limit of existing measuring equipment. The induced loss in sample 11, Table 4.18, which is 2.5 dB in the fiber, could be partially due to experimental error and partially due to damage in the optical cladding occurred during the pulling of the fiber through a conduit with several 90° bends. The induced loss in sample 3, Table 4.18, is 3.7 dB, which is within the experimental error due to the short length of the fiber.

TABLE 4.18

SAMPLE	INDUCED OPTICAL LOSS 24 HOURS AFTER IRRADIATION		ACCUMULATED DOSE 2		FIBER LENGTH (meters)	FIBER TYPE
	at .79 μ	(dB/km) at .82 μ	RADS	N/CM		
1	-13	-.49	1.15×10^4	1.34×10^{10}	300	Silicone B
2	-1.31	-1.11	1×10^4	1.73×10^{10}	274	Silicone A
3	+3.7	+3.67	1.6×10^5	1.3×10^{10}	40	Silicone A
4	.6	.7	2.7×10^5	5.3×10^{10}	40	Silicone B
5	-.04	-.23	1.0×10^3	1.2×10^{10}	950	Silicone A
6	-.32	+.25	8.9×10^2	3.4×10^9	854	Silicone B
7	.98	+1.5	8.3×10^2	5.3×10^9	299	Silicone A
8	-.44	-.38	5.1×10^2	1.7×10^9	877	Silicone A
9	-.14	-.07	8.1×10^2	-	770	Silicone B
10	+1.22	+.61	1.8×10^5	-	99	Silicone A
11	25.0	20.6	2.7×10^5	-	94	Silicone B

Based on the results outlined in Table 4.18, it can be concluded that total recovery took place with 24 hours after irradiation to doses as high as 2.7×10^5 rads.

4.11.3.3 Cable Irradiation

Short sections of the 3 cable designs were irradiated to a high mix flux dose (1.27×10^5 rads of gamma + 4.4×10^{10} neutrons/cm²) for visual inspection and mechanical integrity testing.

The irradiation doses and test conditions for the cables and two long fibers are shown in Table 4.19. No signs of any degradation were visible.

4.11.3.4 Conclusions

It is possible that defect sites are created on the fiber surface during the drawing process which can be saturated during the initial irradiation. These saturated defect sites will not be available to take part in process of electron traps and positive hole formation, and hence lead to lower radiation induced losses in the preirradiated fibers. The following conclusions are offered:

1. The plastic clad silica fibers showed saturation of the radiation induced optical loss in the dose range from 74 to 10^5 rads.
2. The preirradiated fibers showed an improved radiation hardness compared to the virgin fibers.
3. To characterize the radiation hardness of a fiber, it is necessary to specify not only the time of the measurement, but also the radiation dose, as the saturation effect was observed for radiation doses

TABLE 4.19
RADIATION EFFECTS IN PLASTIC CLAD SILICA FIBERS AND CABLES
NEUTRONS AND GAMMA MIXED FLUX PULSED IRRADIATION

TEST NUMBER	1	2	3
Fiber Type Intrinsic Loss	SS2/Sylgard/PFA 18 dB/km	SS2/Shin Etsu/PFA 5.8 dB/km	3 Types of Cables
Induced Optical Loss 24 Hours After Irradiation (dB/km)	-.23	-.07	Loss not measured No visible degradation
Absorbed Gamma Dose using TLD in μC in rads	11.6 .99 x 10^3	9.514 .81 x 10^3	1493.5 1.27×10^5
Neutron Dose/cm ² Neutrons with energies >10 Kev	4×10^9 E	4×10^9 E	4×10^{10}
Exposure Time in Sec.	5.5	5.5	19.8
Shield Thickness	1" Pb	1" Pb	No Pb
Fiber Length	950 m	770 m	2 ft. sections
E = estimated			

as low as 74 rads. The induced optical loss after a specified time in dB/km-rad versus dose in rads should be calculated for each fiber type. From this plot the induced optical loss can be calculated for any dose level within the working curve limit.

Preirradiating Plastic Clad Silica Fibers May
Improve Its Radiation Hardness

To study this effect, further work is needed to establish whether the improvement in the radiation hardness persists over an extended period of time, or whether it is just a transient effect.

It is also important to study and establish the optimum radiation levels to improve the radiation hardness without any adverse effect on the mechanical integrity of the fibers or the cables.

5.0 COMPARATIVE COST-FIBER OPTIC VS. CONVENTIONAL METALLIC CONDUCTOR

One of the objectives of this contract was to develop a fiber optic cable that will be cost competitive with conventional cables when manufactured in large volumes. This section briefly compares the dimensional characteristics and projected costs of cables developed under this contract with the presently used conventional CX 4566 conductor.

A comparison of dimensional characteristics for both cable types is shown in Table 5.1.

TABLE 5.1

	<u>CENTRAL STRENGTH MEMBER F.O. CABLE</u>	<u>CX-4566</u>
Diameter	.250"	.503"
Weight	30 kg/km	219 kg/km
Length/Spool	1 km	76 meters

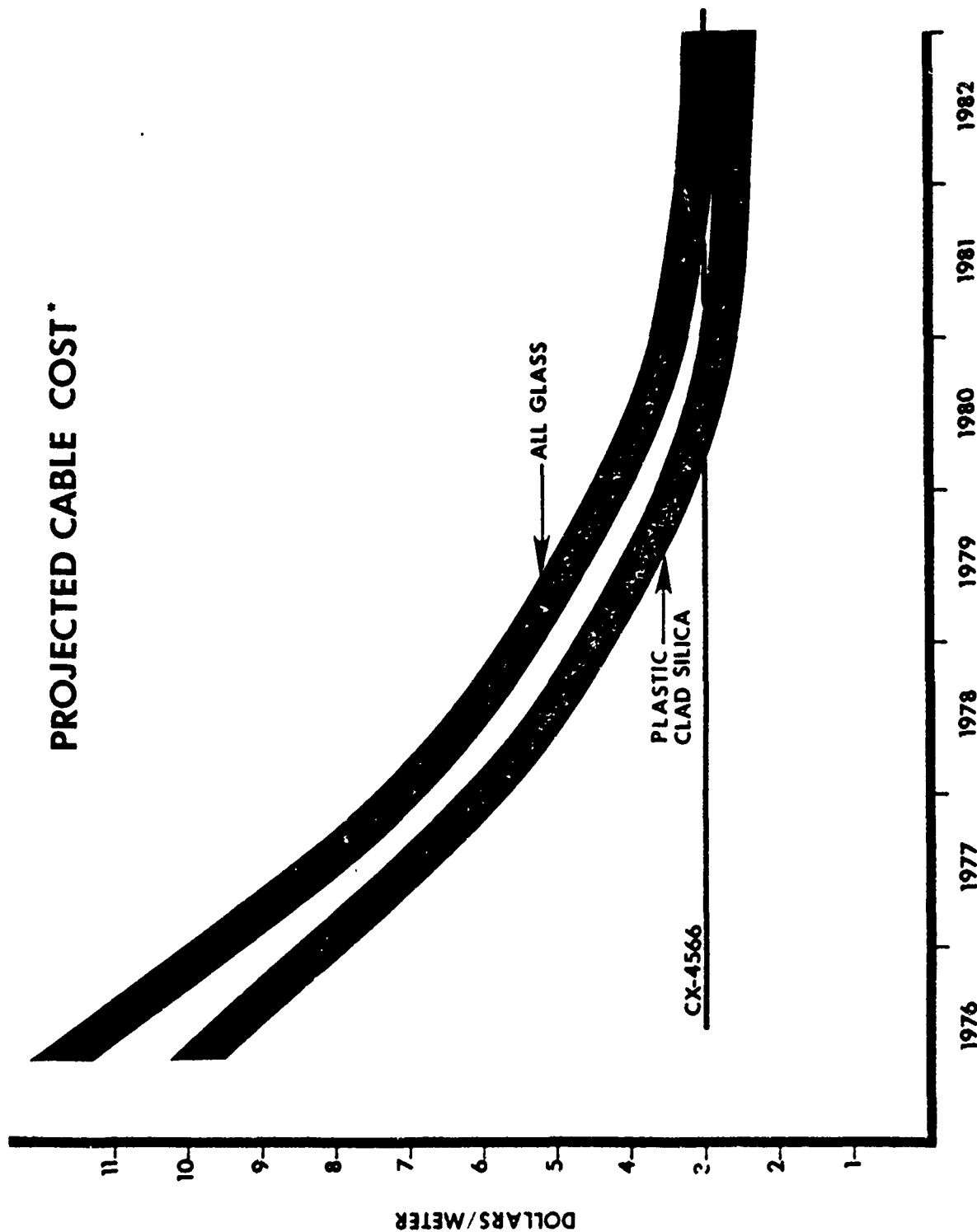
The above data clearly shows the space and weight savings offered by fiber optic cables.

Fiber optic cables similar in structure to those developed under this program which incorporate 6 plastic clad silica fibers and have an attenuation of <20 dB/km, are commercially available for \$9.90/meter. Comparable CX-4566 cable (26-pair) is priced

lower at approximately \$3.00/meter in similar quantities (10-20 km). Figure 5-1 presents a forecast of comparative costs through 1982 and clearly shows that through planned improvements in optical fiber and cable fabrication equipment and processes, fiber optic cables with plastic clad silica fibers will be cost competitive with conventional conductors within 3-5 years. By that time, fiber making processes will allow significant reductions in labor resulting in fiber costs that approach the cost of raw materials. Progress toward the cost reduction of all-glass fibers is also expected to be great during the 1979-1982 time frame.

The cost projections in Figure 5-1 were made on the basis of 1977 dollars, hence a flat line is shown for CX-4566. Inflationary effects will result in progressively higher CX-4566 costs, and reduce the fall off of the cost of optical fiber cable. In any case fiber optic cables are expected to offer cost savings by 1981-1982.

A comparison of projected costs for all glass vs. plastic clad silica fibers indicates that the difference will narrow significantly by the 1981-1982 time frame.



*COST PROJECTIONS ASSUME THE EMERGENCE OF SUBSTANTIAL MARKET SUPPORT FOR MANUFACTURING. AS WITH ALL SUCH PROJECTIONS, THEY SHOULD BE REVISED AS FIRM DATA BECOMES AVAILABLE

Figure 5-1

6.0 CONCLUSIONS AND RECOMMENDATIONS

As part of the "Low Cost Fiber Optic Cable" contract, cables were produced which meet most of the requirements for tactical field applications. The requirements specified in the contract are compared with the achievements in Table 6.1. Results indicate that with further development, all requirements can be met. Specific conclusions reached from the present effort and suggestions for additional effort are discussed in the following sections.

6.1 Conclusions

Based upon the development and evaluation effort, the following conclusions have been reached:

1. Rugged optical fiber cables employing plastic clad silica fibers can be fabricated with optical attenuation less than 10 dB/km.
2. Impact resistance of optical fiber cables, although improved over cables produced earlier, still falls short of the MIL-C-13777 requirement of 200 impacts at 5 ft-lbs.
3. Optical fiber cables can be fabricated with tensile strengths required for field applications.
4. Cyclic bending and twisting have no adverse effects on the optical continuity of optical cable models.
5. Cable design can affect the performance of optical fiber cables after temperature cycling. Designs ECOM-1, ECOM-2, and ECOM-3 showed no significant increase in attenuation while Design ECOM-1A showed a significant increase in three of six fibers.

6. Cable attenuation may be affected by long-term exposure to high levels of moisture. Average attenuation increases of 4-5 dB/km were measured. However, since some of the fibers tested did not exhibit a significant loss increase, it is expected that the effect of moisture on loss can be alleviated.
7. Optical fiber cables can be fabricated with fungus resistant materials commonly used in conventional metallic conductor cables.
8. Irradiation of fibers causes a significant short term increase in attenuation. However, pre-irradiation may produce radiation hardened fibers.

TABLE 6.1
PROGRAM ACHIEVEMENTS

<u>PHYSICAL:</u>	<u>GOAL</u>	<u>ACHIEVEMENT</u>
Length	1/3 - 1 km	1 km+
Number of fibers	6	6 & 7 fiber cable fabricated
Size	.250 inch	.240 inch
Weight	100 lbs/km	66 lbs/km
<u>OPTICAL:</u>		
Attenuation	50 dB/km required	<10 dB/km @.79 microns
	20 dB/km desired	<13 dB/km @.82 microns
Numerical Aperture	>.27	.30
<u>MECHANICAL:</u>		
Tensile Strength	400 lbs	400 lbs.
Vibration, Temperature Cycling, Moisture Resistance, Immersion	MIL-STD-202	No appreciable degrada- tion
Fungus Resistance	MIL-STD-810	No growth
Flexing	MIL-C-13777 2000 cycles	>2000 cycles
Twist	MIL-C-13777 2000 cycles	>2000 cycles
Impact	MIL-C-13777 5 ft/lbs 200 impacts	1.5 ft/lbs., 200 impacts
<u>NUCLEAR SURVIVABILITY</u>		
10^3 - 10^5 Roentgens	<50 dB/km increase 10	55 dB/km average increase 10 sec after
10^{12} - 10^{14} Neutrons/ cm ²	sec after dose	dose Min=5 dB/km Max=175 dB/km

6.2 Recommendations

During the course of the low cost cable development program, it was determined that low cost plastic clad silica fiber cables could be fabricated to satisfy most of the optical, mechanical, and environmental requirements of Army tactical use. A number of areas were identified for further effort, both in fiber and cable fabrication and evaluation. The following are recommendations for further study:

1. Cable performance under actual field conditions should be studied. Cables should be strung from poles using conventional stringing techniques in order to determine long term tension effects on attenuation and mechanical integrity. Roadway survival testing should be accomplished to determine effect of vehicular traffic. Continuity and/or attenuation should be measured at regular intervals.
2. Impact resistance should be improved by revisions in cable design. Emphasis should be placed on strength member design and jacket material selection.
3. Mechanical evaluations (MIL-C-13777F) should be conducted at temperature extremes to determine cable survival capability.
4. Additional temperature cycling should be conducted on designs that employ MYLAR^R tape to determine the source of increased loss.
5. Additional testing should be conducted to verify the effects of moisture on attenuation. Longer lengths of cable should be evaluated and, if necessary, additional moisture barrier provisions should be incorporated into cable designs.
6. Extensive radiation testing should be performed to determine the causes of induced losses and to

verify the finding that indicates "first-dose hardening" of plastic clad silica fibers.

7. Experiments should be conducted to reduce excess cabling losses. Investigation should include stranding techniques, use of monofilament fillers, tape effects, fiber buffers, and strength member surfaces.

APPENDIX A
CABLE TEST PLAN

1.0 OPTICAL TESTS

1.1 NUMERICAL APERTURE (NA) AND ATTENUATION

1.1.1 Specifications

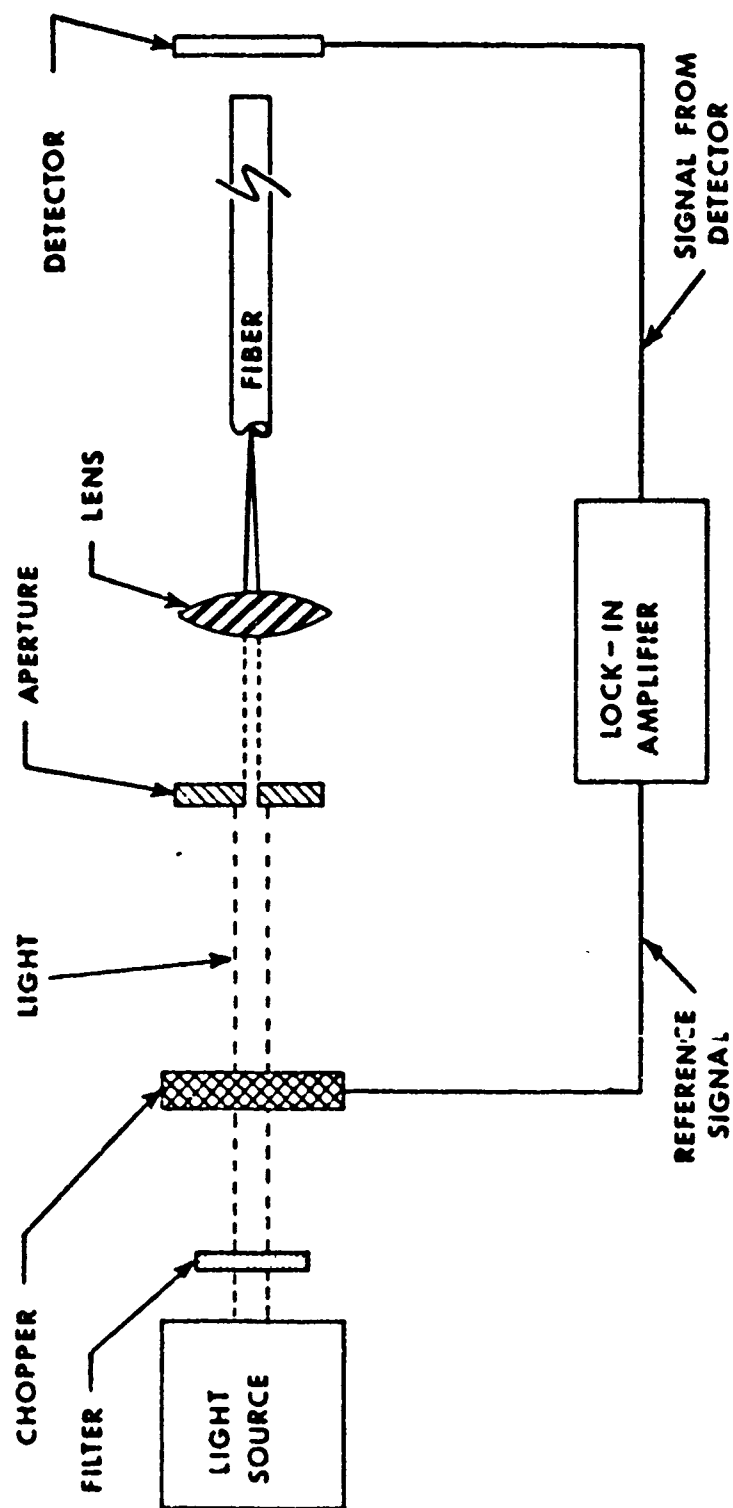
- A) Wavelength: 6,000 - 10,000 Angstroms
- B) Attenuation: 50kB/km (required)
20dB/km (desired)
- C) Numerical Aperture (NA): .27 minimum at one kilometer length

1.1.2 Definition of Test

The test procedure will measure transmitted optical power as a function of the injection numerical aperture (injection cone angle), for long and short lengths of fiber. From this data the attenuation in dB/km will be calculated and an effective numerical aperture will be defined by the Collection Loss (CL) method.

1.1.3 Test Equipment and Procedure

The optical equipment to be used in this test provides for injection numerical aperture control by focusing a collimated beam of filtered light onto the fiber through a photographic lens with a set of fixed F stops ranging from 0.95 to 16 in multiples of approximately 1.4. The voltages



ATTENUATION MEASUREMENT EQUIPMENT

corresponding to detected fiber optical output power at wavelengths 6500, 8300, and 10,500 Angstroms at .124 NA and at 7900 Angstroms at .124, .243, and .336 NA (corresponding to F/4,2, 1.4) will be recorded for both the long fiber length (1/3, 1/2 or 1 km) and the short length (1 to 2 meters).

1.1.4 Data Reduction

The Collection Loss method (CL) is used to reduce the data for 7900 Angstroms as follows:

- A) For each injection NA the total insertion loss (TIL) is calculated in dB;
- B) The fiber attenuation is calculated by dividing the total insertion loss (TIL) for lowest NA (.124) by the fiber length in kilometers;
- C) The collection loss (CL) at each of the higher NA's (.243 and .336) will be calculated by subtracting TIL (.124) from each TIL for the respective higher NA's;
- D) The fiber effective NA will be found by interpolation of the CL to find the NA for which CL = 1 dB, unless the CL at .336 is less than 1 dB, in which case the fiber effective NA will be assumed to be .336.

The attenuation at 6300, 8200 and 10,500 Angstroms is calculated by steps A and B only.

1.1.4 Test Results Reporting

The following data will be reported:

- A) Fiber (cable) net length,
- B) The attenuation for each wavelength and the effective NA at 7900 Angstroms.

1.1.5 Test Facility and Personnel

ITT-EOPD loss measurement equipment and personnel.

1.2 DATA TRANSMISSION

1.2.1 Specifications

- A) Bit Rate: 20 megabits/sec
- B) Rise and Fall Times: 4 nanoseconds
- C) Pulse Flatness: 3 dB pk-pk from voltage output level.

1.2.2 Definition of Test

The test procedure will measure the pulse spreading in the fiber from an input pulse which is much narrower than the output pulse.

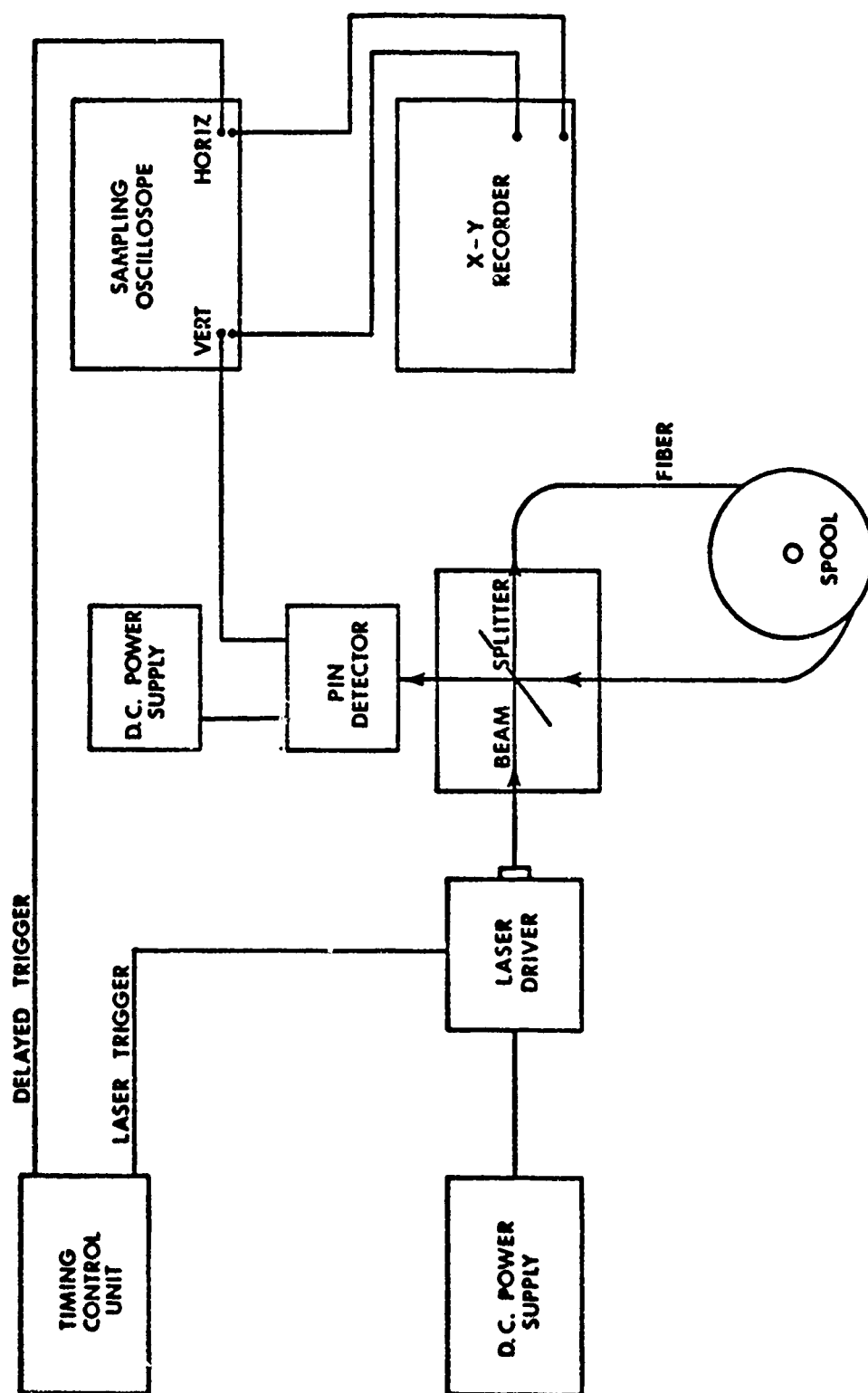
1.2.3 Test Equipment

The equipment to be used in this test consists of:

- A) A pulsed GaAs laser with central emitting wavelength in the neighborhood of 8200 Angstroms;
- B) Appropriate timing and delay electronics;
- C) Pulse detection electronics consisting of either a PIN photodiode (risetime approximately 0.4 nanoseconds) or an avalanche photodiode (somewhat slower than the PIN but with less than 4 nanosecond rise and fall times at optical input powers well below saturation levels), a 0.1 MHz to 1.3 GHz pulse amplifier (gain = 20 times), and a sampling oscilloscope.

1.2.4 Test Procedure

The optical output from the laser source will be collected, collimated and refocused with a magnification of approximately 1 (one) using standard optics. The optical pulse will be injected into the fiber at the image of the source and the fiber output pulse will be detected using the sampling oscilloscope. A permanent record of the output pulse will be made. The optical output from the fiber with the laser operating just below threshold will be recorded on the same permanent record. The net laser pulse will be taken as the difference between these two curves. A similar record will



DISPERSION MEASUREMENT EQUIPMENT

be taken for:

- A) The pulse through a short length of fiber, or
- B) A sample of the pulse before injection into the fiber.

The 3 dB and 10 dB pulse widths of the output and input pulses will be measured from the permanent records.

1.2.5 Test Results Reporting

The 3 dB and 10 dB widths of both the input and output pulse will be reported.

1.2.6 Test Facility and Personnel

ITT-EOPD pulse dispersion equipment and personnel will be utilized.

2.0 MECHANICAL TESTS

2.1 CABLE TENSILE STRENGTH

2.1.1 Specification

400 lb. load for 1 minute

2.1.2 Definition of Test

The test will monitor the number of transmitting fibers before, during, and after application of a 400 lb. load to

a 61 cm (2 ft.) test section (gage length) for 1 minute. The cable elongation will be measured and jacket slippage will be monitored.

2.1.3 Test Equipment

The test will be performed using sheaves, rope and cable, a tension scale, posts, and a cable jack to apply and measure the tensile load to the cable. Each sheave consists of 2 steel plates, 1" x 3" x 24" connected to 2 U-shaped strips of steel with cross-section dimensions of 1/4" x 1". The cable is gripped between the plates by tightening 8 1/4" steel bolts. A tape measure canister attached to one sheave with the tape attached to the other sheave will measure sample length and elongation.

Optical monitoring is accomplished using a standard microscope illuminator.

2.1.4 Test Procedure

A length of cable sufficient for the required number of test lengths will be prepared for illumination by removing the jacket on one end and preparing individual fibers by the diamond scribe and pull technique. These fibers will be gathered into a loose bundle and placed in the focused

beam of the microscope illuminator. The opposite end of the cable is placed in the sheaves with a sufficient length protruding to allow for preparation of the observation end by removal of a short jacket section and separating the fibers sufficiently for comfortable viewing and resolution at a distance of approximately 10 feet. The test section between the sheaves will be marked with masking tape to allow monitoring for jacket slippage or cable slippage in the sheaves. The number of transmitting fibers and the time will be recorded before and after tightening the sheaves. The starting time for application of the load will be noted and the load applied as rapidly as practical with the equipment used to the 400 lb. level; the time at attaining 400 lb. load will be noted and the load maintained for 1 full minute then released at as fast a rate as practical - but not instantaneously. The time of return to zero load will be noted. Fiber continuity will be monitored and noted throughout the test, as well as indications of jacket or cable slippage, and total test section length.

At the end of the test the cable will be cut between the sheave and the illumination end at a sufficient distance from the sheave to eliminate jacket slippage regions. A section of cable starting with the new end will be inserted

into the sheaves and the test repeated as required.

If there are one or more apparent breaks after test the total test section will be examined optically to determine the break location. Coincidence of fiber breakage with jacket bunching due to jacket slippage will be noted. The number of breaks in the cable test section will be considered as the number of breaks occurring in the gage length only.

2.1.5 Test Results Reporting

The gage length, % elongation at 400 lbs. load, and the number of broken fibers will be reported for each test. The occurrence and location of jacket slippage will be reported.

2.1.6 Test Facility and Personnel

ITT-EOPD facilities and personnel will be used.

2.2 CABLE IMPACT RESISTANCE (MIL-C-13777F)

2.2.1 Specification

200 impacts with a 10 lb. weight from 6" (1" diameter hammer).

2.2.2 Definition of Test

Test will be performed as per MIL-C-13777F with the following exceptions:

- A) Optical monitoring of fiber breakage as per tensile strength tests (2.1) instead of electrical tests;
- B) Testing on one continuous length per 2.1.4;
- C) A force-distance product of 1.75 ft.-lbs. will be used on type I and II cable designs;
- D) A force-distance product of 1.00 ft.-lbs. will be used on type III cable design;
- E) Tests to be at room temperature only.

2.2.3 Test Procedure

As in MIL-C-13777F with above noted exceptions.

2.2.4 Test Results Reporting

The cumulative number of broken fibers for all samples of each cable type will be reported as a function of number of impacts. The maximum, minimum and average number of fiber breaks per cable after 200 impacts will be reported for each cable type.

2.2.5 Test Facilities and Personnel

Tests will be performed at ITT-Surprenant Division, Clinton, Mass. Testing will be conducted by ITT-Surprenant and ITT-EOPD personnel.

2.3 CABLE TWIST TEST

2.3.1 Specification

2000 cycles at loading per MIL-C-13777F.

2.3.2 Definition of Test

Test will be performed as per MIL-C-13777F with the following exceptions:

- A) Optical monitoring for fiber breakage as per tensile strength tests (2.1) instead of electrical tests with the possible addition of a detector and strip chart recorder;
- B) Testing on one continuous length per 2.1.4;
- C) Room temperature only.

2.3.3 Test Procedure

As in MIL-C-13777F with above noted exceptions.

2.3.4 Test Results Reporting

The cumulative number of broken fibers for all samples of each cable type will be reported as a function of the number of twist cycles.

2.3.5 Test Facilities and Personnel

Tests will be performed at ITT-Surprenant Division, Clinton, Mass. Testing will be conducted by ITT-Surprenant and ITT-EOPD personnel.

2.4 CABLE BEND TEST

2.4.1 Specification

2000 cycles at loading per MIL-C-13777F.

2.4.2 Definition of Test

Tests will be performed as per MIL-C-13777F with exceptions as noted in 2.3.2, with the additional exception that tests will be performed with a 5/8" radius mandrel.

2.4.3 Test Procedure

As in MIL-C-13777F with noted exceptions.

2.4.4 Test Results Reporting

The cumulative number of broken fibers for all samples of each cable type will be reported as a function of the number of bend cycles.

2.4.5 Test Facilities and Personnel

Tests will be performed at ITT-Surprenant Division, Clinton, Mass. Testing will be conducted by ITT-Surprenant and ITT-personnel.

3.0 ENVIRONMENTAL TESTS

3.1 VIBRATION (MIL-STD-202D, METHOD 204B)

3.1.1 Specifications

- A) Test Condition: A (per STD)
- B) Test Sample Length: Unspecified
- C) Mounting Method: Unspecified

3.1.2 Definition of Test

This procedure will examine the effect of vibration on fiber integrity in the cable. Integrity will be determined by the number of fibers transmitting after the test.

3.1.3 Test Equipment and Procedure

The vibration test equipment for this test will be chosen to conform to MIL-STD-202D, Method 204B, Test Condition A. A suitable length of fiber (on the order of 25 to 50 cm), previously checked for continuity will be suspended tautly between two suitable clamps spaced appropriately. The tests will be run with the vibration motion applied transverse to the cable for 12 test cycles. The clamping fixture will be changed to allow motion parallel to the cable axis and a second sample tested in this geometry for 12 test cycles. The cable sample will then be examined optically for broken fibers and visually for any mechanical failure.

3.1.4 Test Results Reporting

The number of transmitting fibers before and after the test for both transverse and longitudinal motion will be reported. Any mechanical degradation for the cable samples will be reported separately for each geometry.

3.1.5 Test Facility and Personnel

Optical evaluation with ITT-EOPD facilities and personnel.
Vibration tests facility undetermined.

3.2 TEMPERATURE CYCLING (MIL-STD-202D, METHOD 102A)

3.2.1 Specifications

- A) Test Condition: D
- B) Measurements: Attenuation

3.2.2 Definition of Test

A cable sample of about 40 to 50 meters length will be measured for attenuation before and after temperature cycling per MIL-STD-202D, Method 102A. The cable sample will be examined for mechanical defects arising from the temperature cycling.

3.2.3 Test Equipment and Procedure

Prior to temperature cycling the attenuation of each fiber in the cable sample will be measured at 7900 Angstroms and .124 injection numerical aperture. The cable length will be examined for any superficial defects and these will be duly noted. The attenuation test will be conducted after the temperature cycling under the same conditions as before. The cable sample will be examined again for any superficial defects and differences noted. If any significant differences in transmission occur the cable will be examined in detail to determine the probable cause - this examination will include cross-sectioning and dissection of the cable, if necessary.

3.2.4 Test Results Reporting

The before and after attenuation of each fiber in the cable sample will be reported. Differences between superficial characteristics before and after will be reported. If a probable mode of degradation can be identified for a significant change in attenuation, it will be reported.

3.2.5 Test Facility and Personnel

Optical and mechanical evaluation with ITT-EOPD facilities and personnel. Temperature cycling facility not yet determined, however several facilities are available.

3.3 MOISTURE RESISTANCE (MIL-STD-202D, METHOD 106C)

3.3.1 Specifications

- A) Test Condition: Cold and vibration sub-cycles to be included
- B) Measurements: Attenuation

3.3.2 Definition of Test

A cable sample of about 40 to 50 meters length will be measured for attenuation before and after subjecting the sample to the environmental conditions specified in MIL-STD-202D, Method 106C. The cable sample will be inspected for defects arising from the environmental exposure.

3.3.3 Test Equipment and Procedure

Prior to the environmental exposure the attenuation of each fiber in the cable sample will be measured at 7900 Angstroms and .124 injection numerical aperture. The cable sample will be examined for any superficial defects and these will be duly noted. After this test and examination the cable ends will be sealed with an epoxy resin to be more or less impervious to moisture penetration through the sample ends. Alternately, the cable ends may be routed

through appropriate feed throughs to the laboratory to prevent moisture penetration. The same test and examination will be conducted after the environmental exposure, as was done before. If any significant changes in transmission occur the cable will be examined in detail to determine the probable cause - this examination will include cross-sectioning and dissection of the cable if necessary.

3.3.4 Test Results Reporting

The before and after attenuation of each fiber in the cable sample will be reported. Differences between superficial characteristics before and after will be reported. If a probable mode of degradation can be identified for a significant change in attenuation, it will be reported.

3.3.5 Test Facility and Personnel

Optical and mechanical evaluation with ITT-EOPD facilities and personnel. Environmental exposure facility not yet determined, however several facilities are available.

3.4 FUNGUS (MIL-STD-810B)

3.4.1 Specification

Per paragraph 3.1.7 of MIL-STD-810B.

3.4.2 Definition of Test

This test is to determine the resistance of the cable jacket to fungi growth.

3.4.3 Test Equipment and Procedure

The test equipment and procedure for this test appear in detail in MIL-STD-810B. A test sample of suitable length (1 to 5 meters) will be delivered to the testing laboratory.

3.4.4 Test Results Reporting

The testing report from the testing laboratory will be the report on test results.

3.4.5 Test Facility and Personnel

Not yet determined, however several facilities are available.

3.5 NUCLEAR SURVIVABILITY

3.5.1 Specifications

A) Exposure:

gamma-radiation - 10^3 - 10^5
Roentgens (Cobalt 60)
neutrons - 10^{12} to $10^{14}/\text{cm}^2$
(1 Mev equivalent)

B) Fiber Attenuation:

≤ 20% increase ten seconds
after end of exposure (ob-
jective)

\leq 1.0 dB/km increase 24
hours after end of exposure
(objective)

\leq 50 dB/km ten seconds
after end of exposure
(required)

C) Cable Survivability: Unspecified but probable
mode of degradation to be
determined if possible.

3.5.2 Definition of Test

This test will consist of exposing an approximately 200 meter sample of fiber and short lengths (on the order of 1 meter) of cable samples to levels of radiation within the limits defined above. Optical monitoring of the fiber sample during and after exposures will be used to determine optical degradation.

3.5.3 Test Equipment and Procedure

Radiation exposure of the samples will be conducted using the Cobalt 60 source (gamma-radiation) and linear particle accelerator (neutrons) at U. S. Naval Research Laboratories, Washington, D. C. Optical monitoring during and after exposure will be accomplished with suitable apparatus available at NRL. The monitoring wavelength will be approximately 8300 Angstroms; injection numerical aperture will be determined at the time of test. Prior to radiation exposure

the fiber will be tested for optical attenuation according to paragraphs 1.1 of this test procedure report. During the exposure phases of the test the optical signal from the monitoring system will be compared to the monitoring signal just before exposure begins to determine the differential changes in loss. After the 24 hour period post-exposure the fiber will again be tested according to paragraph 1.1 of this test procedure report.

3.5.4 Test Results Reporting

A separate test report for the fiber sample subjected to each radiation source will consist of:

- A) The before and after total attenuation measurement made according to procedure 1.1.3 and data reduction 1.1.4;
- B) The differential attenuation at 10 seconds after the end of exposure;
- C) The differential attenuation at 24 hours after the end of exposure.

Degradation effects in the cable samples will be reported.

3.5.5 Test Facilities and Personnel

Both ITT-EOPD and NRL facilities and personnel will be used in this test with ITT personnel participating in the NRL phase of the test.

SUMMARY OF TESTS

Test	#Samples Tested from		Optical Tests				Applicable Document
	Preliminary Cable Models	Final Cable Models	Atten. &/or NA	Diff. Atten. 8300 Å	Atten. 7900 Å	Pulse Trans.	# Fibers Trans.
Optical Attenuation 7900 Å 4-λ's Effective NA	(each cable) 4 (5) fibers 1 fiber 1 fiber	Same as Preliminary Models	XXX XXX XXX				
Dispersion	1 fiber					XXX	
Mechanical Tensile Load	3 ea. design	3 ea. design ²					XXX
Impact	9-18 ea. design ¹	6 ea. design ²					MIL-C-13777F
Twist	3 ea. design	3 ea. design ²					MIL-C-13777F
Bend	3 ea. design	3 ea. design					MIL-C-13777F
Environmental Vibration		2 ea. design (approx. 45 cm)					MIL-STD-202D METHOD 204B(A)
Temperature Cycling	1 ea. design (40 meters min)	1 ea. design ² (40 meters min)			XXX		METHOD 102A(D)
Moisture Resistance	1 ea. design (40 meters min)	1 ea. design ² (40 meters min)			XXX		METHOD 106C (incl 7a & 7b)
Fungus		1 ea. design (1 meter)					MIL-STD-810B
Nuclear Gamma		200 meter fiber 1 meter ea. cable design		XXX			
Neutron		same		XXX			

1. These tests were performed on sample model runs (reported in the December Progress Report under this contract).

2. These tests will be performed only if significant design changes occur between preliminary and final models.

APPENDIX B
ATTENUATION AND DISPERSION

ATTENUATION AND DISPERSION

ECON-3

336 Meters

ATTENUATION

WAVELENGTH
(microns)

Fiber No.

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>
.65	8.0	8.5	8.3	9.0	8.0	10.4	10.7
.79	6.0	6.8	6.3	7.1	6.3	8.3	8.3
.82	10.5	10.7	10.7	10.8	10.4	12.3	12.5
1.05	16.6	15.8	17.0	17.3	16.1	19.6	17.5

B-1

DISPERSION

(ns/km, 3 dB point)

21	-	-	-	-	-	-	17
----	---	---	---	---	---	---	----

ATTENUATION AND DISPERSION

ECOM-1

324 Meters

<u>WAVELENGTH</u> (microns)	<u>ATTENUATION</u>					
	<u>1</u>	<u>2</u>	<u>3</u>	<u>Fiber No.</u>		<u>6</u>
				<u>4</u>	<u>5</u>	
.65	11.8	10.6	10.0	10.3	9.9	10.2
.79	8.5	7.9	7.4	7.6	7.5	7.5
.82	12.4	11.7	11.5	7.7	11.4	11.5
1.05	20.1	18.0	18.2	18.8	18.5	18.2
<u>DISPERSION</u>	21.6	-	-	-	-	22.4

(ns/Km, 3 dB point)

ATTENUATION AND DISPERSION

ECOM-3

1140 Meters

<u>WAVELENGTH</u> (microns)	<u>ATTENUATION</u>							
	<u>1</u>	<u>2</u>	<u>3</u>	<u>Fiber No.</u>		<u>5</u>	<u>6</u>	<u>7</u>
				<u>4</u>				
.65	19.2	19.7	26.3	21.3		19.9	22.1	19.1
.79	14.9	15.8	24.3	17.0		16.5	17.8	15.1
.82	18.6	19.9	29.0	21.2		20.8	22.0	19.3
1.05	26.4	28.0	40.0	29.3		30.2	31.1	26.7
<u>DISPERSION</u> (ns/Km, 3 dB point)	28.7	-	-	-		-	-	26.0

ATTENUATION AND DISPERSION

ECOM-1

1052 Meters

ATTENUATION

WAVELENGTH

(microns)

Fiber No.

1

2

3

4

5

6

.65

25.4

24.1

20.7

20.1

19.5

20.3

.79

19.3

18.2

18.0

18.1

15.8

17.2

.82

23.2

22.1

22.5

22.5

19.8

21.4

1.05

32.9

31.6

33.6

32.7

29.9

31.1

DISPERSION

(ns/km, 3 dB point)

25.1

-

-

-

32.8

-

ATTENUATION AND DISPERSION

ECOM-1

509 Meters

<u>WAVELENGTH</u> (microns)	<u>ATTENUATION</u> Fiber No.					
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>
.65	11.0	9.6	10.4	9.9	11.8	10.5
.79	8.8	7.3	7.9	7.7	8.7	7.6
.82	12.7	11.1	11.6	11.6	12.7	11.5
1.05	19.7	18.1	18.6	18.2	20.1	18.2

DISPERSION

(ns/Km, 3 dB point)

21.0 20.6

ATTENUATION AND DISPERSION

ECOM-3

520 Meters

WAVELENGTH (microns)	ATTENUATION							
	1	2	3	Fiber No.		5	6	7
				4				
.65	8.1	8.4	8.7	8.8		9.9	8.2	15.9
.79	6.0	6.6	6.5	6.6		7.9	6.5	10.6
.82	9.7	10.2	10.5	10.6		11.9	12.2	13.8
1.05	14.3	16.2	16.0	16.4		19.2	15.9	16.7

DISPERSION (ns/Km, 3 dB point)

- - 22.1 - - 14.4

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